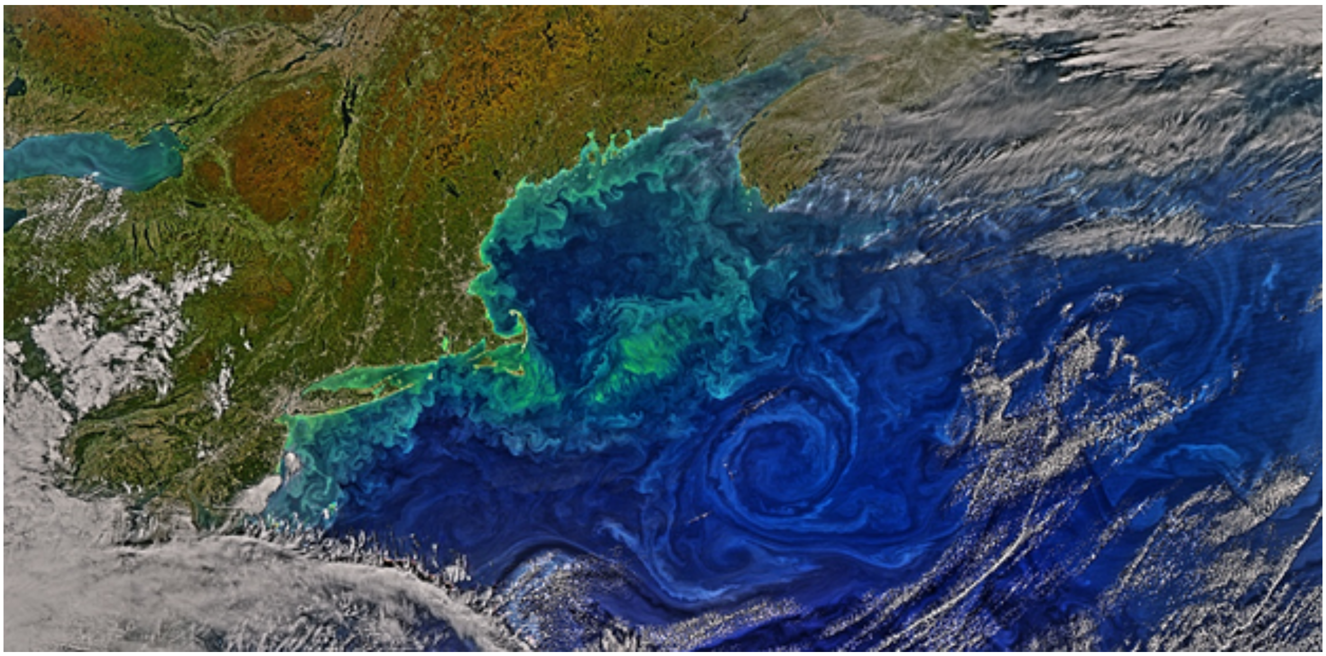
EARTH'S LIVING OCEAN

THE 2017-2027 ADVANCED SCIENCE PLAN FOR NASA'S OCEAN BIOLOGY AND BIOGEOCHEMISTRY RESEARCH



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Dear Reader,

Our Earth is home to over seven billion people. The ocean covers 71% of the Earth's surface, and global Earth-observing satellites allow us to see a view of our Earth and its ocean about every two days. The beauty of our ocean planet is profound and its importance to humanity, our health, and economy is staggering. As of 2010, 80% of the world's population lives within 60 miles of a coast. Fourteen percent of U.S. counties that are adjacent to the coast produce 45 percent of the nation's gross domestic product (GDP), with close to three million jobs (one in 50) directly dependent on the resources of the oceans and the Great Lakes. The Food and Agriculture Organization of the United Nations estimates that fisheries and aquaculture assure the livelihoods of 10-12% of the world's population, with more than 90% of those employed by capture fisheries working in small-scale operations in developing countries. From jobs to food to recreation to regulating climate, the ocean is vital to all life on Earth.

Comparison of our Living Earth to nearby planets exposes a stark contrast to our Earth's habitability. Satellite sensors have revolutionized our perceptions of the ocean environment and our understanding of the linkages among the ocean and other components of the Earth system. Satellite observations have revealed a diversity and complexity in ocean ecosystems that had not been appreciated through traditional oceanographic approaches.

The explosive growth of human populations along coastal margins now places increasing pressure on these dynamic ecosystems, modifying natural processes and, in many cases, putting life, health, and property at risk from hazards inherent to the ocean. Despite this profound realization, the oceans remain largely unexplored, with many discoveries waiting to be made. The past four decades have given us only a brief glimpse of a constantly changing Earth system, in which natural and human factors interplay. We have learned that scientific observations from the vantage point of space help solve important global and regional problems. Advanced technologies and frequent, repeated satellite observations, as well as robust field and laboratory measurements of the ocean are essential to our ability to observe and predict changes.

NASA is leading national and international efforts to define future space technologies and missions. In this spirit, NASA's Ocean Biology and Biogeochemistry (OBB) program scientists engaged the research community in an effort to develop advanced scenarios and strategies to address the important science questions yet to be answered by the program. A working group of experts summarized the state of the science and collected research community comments both electronically and during presentations at a series of national and international meetings.

This report is the product of these efforts. It outlines a strategy for NASA to lead in the scientific application of remote sensing technologies for the exploration and understanding of biological and biogeochemical processes of our oceans. This effort is absolutely critical to ensure the sustainability of our ocean economy, protect our home planet, and inspire the next generation of explorers and scientists, mathematicians and writers. The report addresses the interplay between chemistry and biology at the scale of the planet, the diversity and resilience of our coastal habitats, hazards that pose risks to the environment and to human communities, and how these processes feedback to global climate. As with the first OBB Advanced Science Plan published in 2007, this new plan addresses advances in science and technology over the last decade. The plan remains a living document that will continue to evolve as improvements in our understanding of ocean processes and our home planet unfold and lead to an *optimal strategy for supporting further science advances. The vision is to fully discover the mechanisms and interactions that sustain life on our ocean planet, reaching for new heights technologically, and revealing the unknown for the benefit of humankind.*

Sincerely,
Paula Bontempi
Chair, Biological Oceanography and Biogeochemistry Working Group (BOBWG)

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EXECUTIVE SUMMARY

Life on Earth exists in a delicate balance supported by the exchanges of energy and materials between the land, the atmosphere, and the ocean. Water is critical in maintaining this balance. Over 96.5% of the water on Earth is contained in the ocean, where life plays a fundamental role in converting energy from the sun and chemicals from the environment into food and other materials that sustain a complex web of life that includes our human societies. The vast expanse of the ocean presents significant challenges in our efforts to characterize how biological, chemical, physical, and geological processes work. It is in our interest to quantify how these processes interact to distribute food and chemical energy around the world. We need to know which organisms capture, store, and release gases, and how these then react with chemicals that affect the composition of the ocean or the atmosphere. We want to improve our skill in assessing how nature works, and in predicting how life will be impacted by extreme events and long-term climate trends. NASA's oceanographic research on the use and application of space-based assets since the 1970's has proven beyond any doubt that the ocean biosphere has been changing over seasonal, interannual and decadal-scale timeframes, and that these changes propagate up and down the marine food webs. Some of these changes are driven by a changing climate. Some of them are the direct result of human activities. These discoveries have raised new fundamental questions that require the expertise and technology of the NASA Ocean Biology and Biogeochemistry (OBB) scientific research program.

To guide the OBB program, a working group representing the scientific community including private, academic, and government sectors has updated the OBB Advanced Science Plan for the 2017-2027 decade. The new plan lays out the observational strategies to address the new probing science questions. These strategies include the development and application of space technologies. This plan includes feedback solicited widely from the broader research community before and during the process of writing this report.

The objectives of the next phase of the NASA OBB research program are defined by the following four questions. These questions are synergistic as they address ecosystem processes linked through complementary space and time scales:

- *What processes drive change in ecosystem structure and biodiversity and how do contemporary changes in these globally expansive ecosystems inform improved management practices, predictions of change, and global ocean stewardship?*
- *How are the diversity, function, and geographical distribution of aquatic boundary habitats changing?*
- *How do carbon and other elements transition into, between and out of ocean pools? What are the quantitative links between ocean biogeochemical cycles and climate?*
- *How can knowledge of the spatial extent, dispersion, intensity, and frequency of transient hazards and natural disasters in the aquatic environment improve forecasting and mitigation?*

These science questions are directly applicable to ecosystem health and services, human health, welfare, recreation, and commerce and can be used to develop and maintain effective strategies for assessing and managing changes to Earth's systems from the oceans, atmosphere and land. Building from these science questions, a portfolio of satellite and airborne missions, field observations, and modeling capabilities are proposed for the OBB program. We feel that the entire portfolio is critical to understanding our home planet in the next decade and have chosen not to prioritize any single strategy or mission. The ecological and biogeochemical processes that operate from local to global scales, the stressors and hazards that they are exposed to, are often linked. Yet they are not all observable with any one technology. Detailed observations at different scales will quantify variations that affect global budgets of elements like carbon and nitrogen, help assess the status of natural resources, while also inform decisions about resiliency and recovery to hazards like severe storms, tsunamis, and oil spills.

These are the technologies that the OBB community recommends investments in:

- Continuity of global ocean spectrometry from polar-orbiting Low-Earth Orbit for phytoplankton biodiversity and productivity measurements;
- A global-observing, ocean-focused satellite Light-detection And Ranging (LIDAR) to provide information about the vertical structure of particulate matter and phytoplankton physiological state;
- Imaging spectrometer observations from geostationary platforms for coastal, inland waters and basin-scale high-temporal coverage of changes in carbon stocks, phytoplankton biodiversity, physiology and productivity, and lateral fluxes of aquatic constituents;
- Combined high spatial, high spectral, high temporal, high signal to noise (H4) observations for coastal aquatic and wetland habitat and biological diversity assessments;
- Portable sensors on orbit and suborbital, including assets on or in the water, for mapping and tracking fine-scale features in aquatic habitats, mid-ocean processes, infrastructure development in coasts and on seabed, and to inform science and responders about transient hazards and natural disasters;
- Field data and campaigns to conduct process studies of aquatic ecosystems and for calibration and validation of satellite imagery; and
- Advanced marine ecosystem modeling (regional and climate modeling) and analysis tools.

The technology for each of the proposed concepts is fairly well developed, and yet additional breakthroughs are required and are within reach over the next decade with focused strategic investments and collaboration with academic and private sector partners. Continued exploration of the ocean biology and biochemistry through NASA's space-based and observational technology will stimulate our ocean economy and improve our health. Ultimately, these investments help ensure our survival on the only planet where we know life exists, and help understand conditions under which other planets may harbor life.

The OBB science questions follow from the NASA Strategic Plan and NASA's Science Mission Directorate goals. The results will be directly applicable to the conservation and enhancement of ecosystem health and services. The answers will promote human health, welfare, recreation, and commerce. As these technologies are developed, they will lead to a range of applications across a spectrum of ocean use and management sectors.

1 GRAND CHALLENGES

The Earth system is a delicate balance among ocean, land, ice, and atmosphere. NASA's oceanographic research from space over the past three decades has revealed synoptic, seasonal to decadal-scale changes in the ocean biosphere. These discoveries raise new questions that now define the course of research for the future. From this scientific foundation, NASA must carefully formulate plans for requisite space-based missions. The resultant next phase of research will extend our understanding of how ocean ecosystems, boundary habitats, elemental cycles, and hazards influence Earth's ecosystem health and services, human health, welfare, recreation, and commerce. NASA's Ocean Biology and Biogeochemistry Research Program will also enable the formulation of effective strategies for assessing, adapting to, and managing climate change through space-based observations and improved Earth System modeling capabilities. Additionally, NASA needs to coordinate with other national and international efforts that are deployed or scheduled to deploy soon in order to address as best as possible the science questions and gaps in understanding. This document is a blueprint for NASA's space-based research of the Earth's living ocean for the next decade.

Expansive Ecosystems

The global ocean dominates the spatial extent of Earth's biosphere. The ecosystems occupying the marine environment are diverse, complex, highly productive, and fragile. Trophic interactions within ocean ecosystems vary from simple food webs involving minimal trophic transfers between photosynthesis, fish, and carbon export, to highly interwoven food webs that recycle nutrients with near perfect efficiency and separate photosynthetic and apex predator production by many trophic levels. Humanity depends on these complex attributes of ocean ecosystems. Some ecosystems play a disproportionately large role in carbon biogeochemistry, some support our largest fisheries, while others are particularly efficient at removing excess nutrients at the land-ocean interface. It is impossible to fully quantify the value of the global ocean to humanity, since such an assessment requires costs for intangibles and non-market products such as the role that ocean plays in atmospheric regulation, carbon storage, global temperature, and its value to human culture and lifestyle. However, assessments have been made of the ocean's annual 'gross marine product' with respect to marketed goods and services, and even for this limited range of benefits values are on the order of a staggering >$2 trillion U.S. dollars per year, with a total 'asset base' of at least $20 trillion U.S. dollars. Alterations in ecosystem composition and productivity impact function, and function determines the human goods and services provided by the ocean. This leads to the overarching challenge question: *What processes drive change in ecosystem structure and biodiversity and how do contemporary changes in these globally expansive ecosystems inform improved management practices, predictions of change, and global ocean stewardship?*

Life on the Edge

Coasts and estuaries, the benthos, the interface between ice and water, and fronts between water masses are all examples of boundary habitats that support complex communities of organisms. They are areas where marked changes take place continuously in the physical, chemical, or geological structure of marine, brackish, and freshwater environments. Physical processes and biogeochemical transformations that affect water properties operate here over short distances of meters to kilometers and over hourly timescales. The phenology of the diverse life forms that grow in these habitats often changes rapidly, from day to day, and over these short distances. These habitats sustain industries including tourism and recreation, energy and mineral extraction, fisheries and aquaculture, agriculture and urban development, and extraction of various marine bio-molecules for increasingly diverse and powerful pharmaceutical products and construction materials. Coastal zones are where the majority of humans choose to live. It is critical that the health and vitality of these areas be sustained to sustain the growth in human population projected for the near and long term. Many of these boundary habitats have been experiencing lasting shifts in marine community composition, productivity, and biodiversity as a result of chronic and acute pressures, derived from changes in climate combined with increasing human activities, some of them occurring far inland. These changes require a new paradigm in scientific observation to address fundamental and applied science problems. *How are the diversity, function, and geographical distribution of aquatic boundary habitats changing?*

Ocean Biogeochemistry and the Earth System

Large quantities of elements common on Earth have their cycles interlinked with life in the ocean. Oxygen, carbon, nitrogen, phosphorus, silica, iron, manganese, and even those elements in minute concentrations in ocean water like cadmium and aluminum, are actively transformed from one form of matter to another by marine organisms. One of the most important processes that sustain life on Earth, photosynthesis, captures carbon dioxide and water to produce organic molecules. This part of the carbon cycle is linked to other elements. Nutrients, for instance, place constraints on production, growth, and other aspects of the life cycle of marine organisms. The inventory of these elements depends on how organisms organize themselves into diverse food webs in different places around the globe. Collectively, elemental cycles sustain the biosphere and influence climate. The surface-to-depth transfer of organic carbon, for instance, is a key control on atmospheric CO_2 on geologic timescales. Climate, in turn, modifies and impacts ocean life and regulates the form and speed of element cycles. The geological record illustrates the dynamic nature of ocean biogeochemical cycles and how these cycles are in a delicate balance with climate. Today, these intertwined systems are also profoundly impacted by humans through both direct manipulation of elemental cycles and via climate change. *How do carbon and other elements transition into, between and out of ocean pools? What are the quantitative links between ocean biogeochemical cycles and climate?*

Transient Hazards and Natural Disasters

Every year, disasters threaten natural environments and human communities around the globe. Life along the coast, property on the waterfront, and commerce in the ocean and in waterways face the formidable forces of nature and increasing threats from accidents or other human-caused problems. Hurricanes, tsunamis, harmful algal and bacterial blooms, sea ice, erosion, floating and submerged debris, and pollution such as derived from nutrients, metals, plastics, organic chemicals and radioactivity represent just a few of the threats across the aquatic landscape that threaten ecosystems and the services they provide. Hazards and disasters can take place within a matter of hours, and many changes have intense impacts on aquatic and coastal resources, destroying life and property, and can affect large geographic areas for long periods of time. Better quantification of the different types of hazards and disasters can assist in damage assessment and aid in recovery to coastal communities. *How can knowledge of the spatial extent, dispersion, intensity, and frequency of transient hazards and natural disasters in the aquatic environment improve forecasting and mitigation?*

2 BENEFITS TO THE NATION AND BEYOND

In subsequent sections of this Advanced Science Plan, we describe scientific motivations, observational requirements, and research activities associated with addressing the Grand Challenges outlined above. However, benefits from this OBB Program Plan for our nation, and all nations, extend far beyond the direct advances made to scientific knowledge and thread through global economies, national security, policy, human health, resource management, food security, navigation, and weather and climate prediction. Aquatic ecosystems provide 20% of annual animal protein to 3 billion people each year, with this value exceeding 50% in some countries. The ability of aquatic systems to continue supporting such demands depends on scientifically-sound management practices supported by advanced observations, such as those described herein. The ocean also generates hundreds of millions of jobs in tourism, fishing, energy, shipping, biotechnology, and other sectors, ranking the ocean as the seventh largest global economy (Figure 1). Advanced observational capabilities outlined in this report contributed to sustaining this vast ocean economy. For the U.S., the 30 ocean and Great Lakes coastal states comprise 57% of land area, but 82% of population and economy. Effective management, monitoring, and protection of marine systems are national priorities, particularly given that employment and population growth in coastal counties is the highest in the nation. The ocean currently generates the largest share of the U.S. natural resources economy (including farming, food production, oil and gas extraction, and forest products) and its share of U.S. employment is as large as that of all these other natural resource industries combined. Again, the security of this economy relies on the types of observational assets and research-based understanding uniquely provided by NASA's OBB Program.

The portfolio of observations outlined in this advanced science plan represents a path forward for assessing value, determining impacts, and detecting change in coastal and estuarine resources to global ecosystems. These capabilities allow monitoring of fisheries and water quality, mapping of sediment plumes, improving protection of sensitive ecosystems (e.g., seagrasses, corals), and developing advanced detection, forecasting, and early warning systems for aquatic threats that impact human health, including harmful algal blooms (HAB) and aquatic pathogens (e.g., fecal coliforms such as *Vibrio* sp.). The economic value of such capabilities is substantial. As examples, coastal HAB events have an estimated cost impact of $82 million per year in the U.S. alone and healthy coral reef systems provide billions of dollars to local economies through recreational industries, restaurants, and other associated businesses.

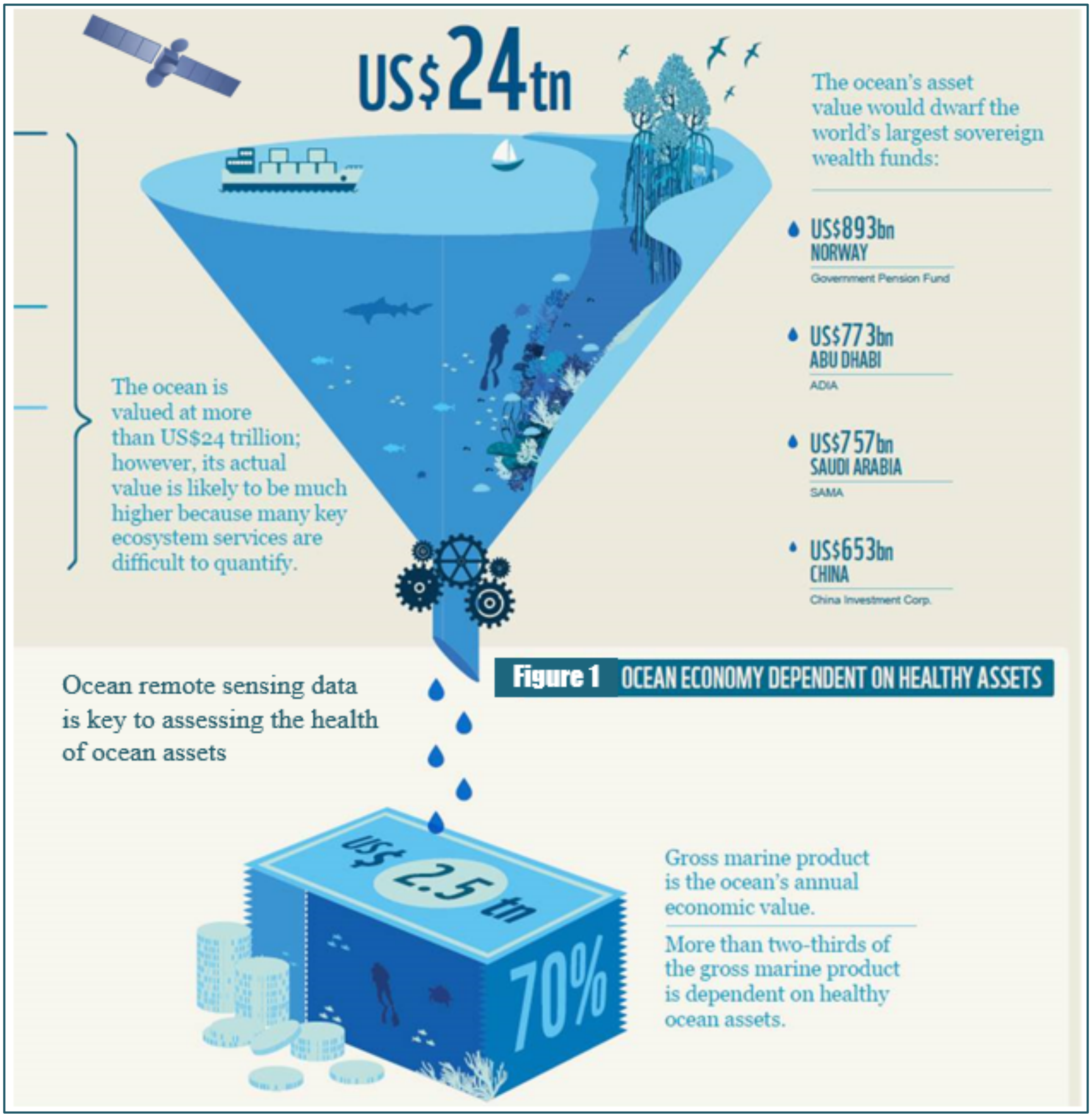

Figure 1: Figure adapted from Hoegh-Guldberg et al. (2015). Reviving the Ocean Economy: the case for action - 2015. WWF International, Gland, Switzerland, Geneva, 60 pp.

Observations outlined in this Advanced Science Plan also improve ecosystem vulnerability assessments and enable improved management of fisheries resources. The value of these later resources is staggering. U.S. commercial fisheries associated with coral reef systems alone has been estimated at over $100 million (National Marine Fisheries Service) and international trade in fisheries contributes $70 billion annually to the U.S. economy (NOAA's State of the Coast). By improving the spectral, spatial, and temporal resolution of observations, significant advances will be realized in understanding spawning habitats and recruitment success, characteristics and changes in species environmental niches and life cycles, factors controlling ocean productivity and variability, and the planning for and impacts of coastal aquaculture. Understanding controls on marine diversity and improving ecological forecasting are required scientific steps, to realize the promise of better living for humans everywhere.

Beyond ecological applications, this Advance Science Plan details capabilities that have other direct benefits to the Nation and globally. The advanced observational assets enable improved monitoring of water quality in estuarine and coastal areas where people swim, fish, recreate, and conduct diverse cultural activities. In many of these regions, clear signs of degradation in water quality have impacted public health and the economy. Nutrient inputs to near-shore aquatic systems cause excessive productivity, or 'eutrophication', and one of the most acute consequences of this eutrophication has been a rise in hypoxia, or 'dead zones,' that kill fish and other marine life. Indeed, there are now over 500 known 'dead zones', with the number increasing most rapidly in the developing world. Such events endanger important ecosystems that provide communities with food.

Improved monitoring of ocean conditions and dynamics is also beneficial to emergency managers and community decision-makers faced with flood, hurricane, volcano, fire, oil spills, and other disasters. These capabilities have significant economic value. For example, the economic cost of the 2010 Deepwater Horizon explosion and oil release in the Gulf of Mexico is estimated at $50 billion and scientific investigations related to this disaster aided in assessment and recovery efforts. Satellite ocean observations of currents and sea ice extent have become increasingly valuable in the shipping industry for navigational purposes as well as developing fuel economy strategies. Satellite ocean observations have also played an important role in human safety, supporting search and tracking assistance for over 8,000 rescued people in the U.S. since 1982.

While the Advance Science Plan presented here is largely focused on aquatic applications, it is important to note that the associated observations also contribute to atmospheric applications by providing improved or sustained measurements of clouds and aerosols. These data are needed by regulatory agencies, resource managers, weather forecasters, and first responders to allow for better assessments of local and regional air quality (a public health application) and better characterization of hazards for issuing disaster warnings (a public safety application). Air quality remains an important concern for human health nationally and globally, and is degrading in many regions. In the U.S., the accumulated economic value of the reduction in air pollution since 1990 is estimated to reach almost $2 trillion by the year 2020 (United States Environmental Protection Agency, 2016). Observational capabilities described herein will contribute significantly to understanding, monitoring, modeling, and predicting changes in air quality and weather. In addition, these measurements have significant value to the aviation industry by providing observations of plume extent and trajectories following volcanic eruptions to allow for rapid adjustments in international aviation flight scheduling and routing.

The broad-reaching benefits of this plan extend well beyond specific science targets. The execution of this plan will inspire exploration and discovery of our home planet. It will provide tangible benefits to the people of our nation and the world by providing data necessary to improve the quality of human life and contribute to job and economic security. Moreover, the technological advances required to achieve the proposed goals will be relevant to homeland security and will foster partnerships between businesses, state and federal partners.

3 State of the Science

Systematic remote sensing of ocean color from space began with the launch of the Coastal Zone Color Scanner (CZCS) in 1978. This sensor provided a first glimpse of what ocean color instruments could provide by generating a time-series of data at selected scenes until 1986. NASA launched the Sea-viewing Wide Field-of-View Sensor (SeaWiFS, NASA/USA) in 1997 which provided climate quality imagery for nearly a decade and a half. Follow-on satellite ocean color instruments included the Moderate Resolution Imaging Spectroradiometer (MODIS)-Terra, MODIS-Aqua, and the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi-National Polar-orbiting Partnership (Suomi-NPP, USA). These sensors have provided two decades of uninterrupted satellite ocean color data of varying quality to generate phytoplankton pigment (chlorophyll-*a*)concentration (also known as ocean plant-like biomass) and primary production estimates. These derived estimates have been extensively used to study ocean biogeochemical cycles and their numerous effects on the global carbon cycle, including seasonal, interannual, and decadal variability. Maintaining the continuity of the high quality, calibrated ocean color imaging record is crucial to understanding the complex interactions and effects of climate variability and change on ocean biogeochemical cycles that span over decades. The success of these overlapping missions has taught us many lessons and led to well-established guidelines for maintaining ocean color data of sufficient quality into the future as required to detect trends and changes with certainty, i.e. what is typically referred to as 'climate quality' in the science community jargon (National Research Council, 2011).

Continuous observation of ocean color is now also recognized as essential to satisfy operational and research societal needs. The Global Ocean Observing System has recognized ocean color as an Essential Ocean Variable (EOV) that supports monitoring of ocean currents, fisheries, and other aspects of ocean ecosystems. At the time of writing of this report in March 2017, there are plans to launch VIIRS on the NOAA Joint Polar Satellite Systems 1 and 2 (JPSS-1 and JPSS-2) satellite missions, with expected launch dates of late 2017 and 2022, respectively. VIIRS provides the important capability to generate first-order estimates of chlorophyll-a concentration with a subset of the MODIS bands. This is applicable over much of the world's ocean to detect fronts and blooms. However, the radiometric quality, number, and position in the spectrum of VIIRS bands are not designed to measure the fluorescence of phytoplankton stimulated by the sun, the subtle differences in color between phytoplankton groups, or to distinguish between living phytoplankton, detritus and colored dissolved organic matter, particularly in coastal zones.

The OBB community has thus recognized that the coarse spectral resolution of the core heritage ocean color satellites, of VIIRS, and of the ocean color satellites launched by other nations is not sufficient to understand the biodiversity of pelagic and shallow benthic communities in the oceans. Different types of phytoplankton, as well as their physiology, play unique roles in climate, biogeochemical cycling, and trophic interactions. The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Mission, planned for launch by NASA in the 2022 timeframe, will fill this gap. Collaboration with the academic and private sectors on nanosatellites (see below) can also help continued observations.

Passive ocean color sensor data, coupled with in situ observations and numerical models, have revolutionized our understanding of ocean processes, their complexity, and their interactions with other parts of the Earth system. Ocean remote sensing allows scientists to effectively 'take the pulse' of our living Earth. Combining different NASA satellite technologies has afforded new scientific insights on how ocean physics and biology are coupled. This laid the groundwork for comprehensive assessments of global ocean primary productivity, the process by which phytoplankton grow and fix carbon and thereby support nearly all ocean ecosystems. NASA's technology has enabled the observation of changes in ocean plant-like biomass and productivity seasonally, annually, and even from day to day. This has led to the discovery of large-scale biological patterns associated with the dispersal of river water, the impacts of El Niño-Southern Oscillation events on changes in fisheries, and the influence of ocean biology on air-sea exchange of carbon dioxide and other gases relevant to air quality and/or climate change.

SIGNIFICANCE OF PACE

The NASA **Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Mission** scheduled to launch in the next decade will provide unparalleled global, space-based hyperspectral measurements of water leaving radiances and associated aerosol and cloud information. Precise measurements in the short-wave infrared wavelengths also will enable advanced methods to remove atmospheric effects as required to yield highly accurate observations of the ocean surface. The PACE Mission will continue a climate data record of high quality ocean color measurements that is still less than two decades in length. PACE represents a major breakthrough in our ability to understand and model global ocean biogeochemical cycles, climate, and trophic interactions. It will provide a hyperspectral dimension to detect absorption, scattering, and fluorescence properties of our global ocean observations that will ideally be continued into future operational climate quality monitoring of ocean color. And, as outlined below, it has many other applications that will benefit the nation.

Interdisciplinary research involving observations from various national and international space-based and ground-based sensors continues to focus on linking data from terrestrial, aquatic, and atmospheric environments of the Earth to study biogeochemical cycling, ecology, climate variability and change, the solid Earth, and the water and energy cycle. NASA's modeling, analysis, and prediction program is focused on integrating interdisciplinary and multi-disciplinary NASA research efforts by supporting pioneering work on climate and ecological model development, as well as their linkage, to improve the nation's ability to manage ecosystems. Continued exploration and research based on new measurements of Earth's living ocean are essential to the goal of working with our international partners to manage global ocean ecosystems while better understanding and enabling adaptation to climate change.

4 SCIENTIFIC IMPERATIVES

This section outlines the four major science themes of the Ocean Biology and Biogeochemistry program for 2017-2027.

4.1 EXPANSIVE ECOSYSTEMS

What processes drive change in ecosystem structure and biodiversity and how do contemporary changes in these globally expansive ecosystems inform improved management practices, predictions of change, and global ocean stewardship?

The scientific community has identified a series of fundamental questions that are directly relevant to the Science Questions and Goals from the 2014 Science Plan for NASA's Science Mission Directorate. The challenge is to implement a strategy that advances basic and applied science in a systematic and timely fashion. The science is scoped to enable solutions to the needs and the impacts of growing human communities around the Earth. Here we outline the challenge and the broad questions that the scientific community needs to address over the course of the 2017-2027 decade.

The Challenge

Aquatic ecosystems are the living communities made up of plants, animals, bacteria, archaea and viruses, and the physical environment in which they are embedded. All of these parts function collectively as a unit, with spatial and temporal variability that we are just beginning to characterize because of the unique observations provided by satellite sensors. Ocean ecosystems provide important benefits to society, what we often call "ecosystem goods and services." These benefits include productive fisheries, pharmaceuticals, and waste processing, as well as the biogeochemical cycling of important elements critical for life on Earth. From a food standpoint alone, over 3 billion people obtain ~20% of their annual animal protein from fish, and in some countries this number exceeds 50%. It is further projected that the contribution of the ocean to global food supplies will increase in the future as agricultural production continues to fall behind human population growth. When broader goods and services are considered, the 'gross marine product' value of the global ocean has been estimated at a staggering >$2 trillion U.S. dollars per year, with a total 'asset base' of at least $20 trillion U.S. dollars. Even such large values fail to capture some of the more intangible and non-market values of a healthy global ocean.

The health and productivity of ocean ecosystems are inextricably linked to the overall health of all life on Earth. These ecosystems are not static in time. They experience diurnal to seasonal changes, and can change from year to year. Some of these changes are regular and predictable, but ocean ecosystems are being perturbed by both natural and anthropogenic factors. We need to understand and quantify the processes governing change in today's marine ecosystems across their global domain in order to reliably predict future change, enable effective ecosystem management, and safeguard their societal benefits for generations to come.

The most important source of energy for oceanic food webs is that derived from the sun. The overwhelmingly dominant contributors to ocean photosynthesis are the microscopic phytoplankton. A fundamental challenge for understanding marine ecosystems, therefore, is to accurately quantify global phytoplankton photosynthesis, its spatial distribution, and temporal change. An associated challenge is quantifying the fate of primary production (i.e., the net result of photosynthesis). Some primary production is rapidly respired back to CO_2, some is converted to the biomass of organisms higher in the food chain (e.g., krill, fish, mammals), and some is lost from the sunlit surface layer to fuel ecosystems deeper in the sea or be buried in sediments where it sequesters carbon for years to millennia. *What are the rates, distributions, and limiting factors of ocean photosynthesis, what processes determine the partitioning of primary production to its varied fates, and how will these characteristics of ocean ecosystems change in the future?*

In addition to overall productivity, plant and animal community diversity plays a critical role in ecosystem functioning. Highly productive ocean ecosystems, such as coastal upwelling environments, tend to have food webs with fewer links between the energy stored by primary producers and that used by higher trophic levels, like fish and humans. Less productive, open-ocean food webs are comparatively more complex, with a wide diversity of plants and animals playing important roles in the cycling and recycling of energy and nutrients. Understanding this diversity globally – i.e., details on the types of animals and plants comprising ocean communities and the different environments that they live in – remains a major scientific challenge. More broadly, this challenge encompasses not only "who is there" but "when are they there." The timing of events at one level of the food chain, such as the succession and climax of an annual phytoplankton bloom, has profound importance to organisms at other levels, some of which evolve migration patterns or life cycle strategies based on historic occurrences of the event. How do we resolve the complex drivers of marine ecosystem structure and phenology to develop more effective strategies for managing marine resources and services, such as fisheries or carbon sequestration?

Aquatic ecosystems comprise complex sets of interactions between organisms and their physical, geological, biological and chemical environment, all within a dynamic physical environment. Changes in currents, temperature, salinity, light, and chemical conditions of the upper ocean play critical roles in shaping the structure, function, persistence, and resilience of an ecosystem. These disturbances of the physical-chemical environment occur over a continuum of space and time scales. Linking disturbance phenomena to ecosystem responses represents a significant challenge for current and future generations of scientists. *What role does disturbance play in shaping ecosystem behavior and how do these interactions vary across disturbance time scales that span from episodic events, such as storms, to gradual changes, such as shifts in global ocean temperature?*

From photosynthetic efficiencies, to trophic energy transfer, to global biogeochemistry, species diversity within marine ecosystems is a defining characteristic. This diversity is closely tied to physical attributes of the ocean environment, and thus to climate. Climate-driven changes in physical forcing, such as during natural El Niño - La Niña events, alter ecosystem composition and productivity, which in turn impact the human goods and services provided by the ocean. Understanding these interdependencies—and how behaviors of today's expansive ocean ecosystems inform us on future change—are grand challenges for NASA's Ocean Biology and Biogeochemistry Program. *How can we best observe, assess, and understand the diversity, trophic structure, productivity,* *and resilience of Earth's marine ecosystems in a world ever changing due to natural and human influences?*

What We Know and Need to Learn About Ocean Ecosystems

The first satellite-based global assessments of surface phytoplankton chlorophyll concentrations were provided between 1978 and 1986 by NASA's Coastal Zone Color Scanner (CZCS). Its successors have provided a global chlorophyll record that has remained uninterrupted from 1997 to this day. These data have had a profound impact on our understanding of global ocean ecosystems and how they are influenced by climate. For example, the first years of the SeaWiFS mission recorded the biological impacts of a massive El Niño to La Niña transition in unprecedented detail. In subsequent years, additional studies have described temporal trends in chlorophyll concentrations for the five subtropical gyres, demonstrated that global variations in chlorophyll are inversely correlated to sea surface temperature (SST) changes in warmer regions, and made advances in distinguishing different phytoplankton functional groups within global ocean ecosystems. Furthermore, the retrieval of surface chlorophyll concentrations from space has provided a critical foundation for improving assessments of global ocean primary production, and even for separating this production into that which is rapidly consumed by surface layer ecosystems and that which is exported to the deep ocean. These are but a few of the many accomplishments enabled by our heritage ocean color satellite missions. Alongside these accomplishments, a new generation of questions has been raised that will require more advanced global observational capabilities to address them.

The traditional focus on chlorophyll, as the primary satellite-retrieved phytoplankton property, reflects a common, first-order assumption that chlorophyll concentration is a reliable index of phytoplankton biomass. This assumption is inappropriate when attempting to detect climate-driven trends in phytoplankton biomass and primary production. In the time since the CZCS mission, major advances have been realized in ocean color analyses, in particular the rise of spectral inversion algorithms. This new generation of algorithms allows for the simultaneous retrieval of phytoplankton pigment absorption, particulate backscatter (bbp), and absorption by colored dissolved organic matter (cDOM). With this new set of retrieved properties and field-based relationships for assessing total particulate carbon and phytoplankton carbon from bbp, important advances have been made regarding the interpretation of temporal trends in ocean color. For example, it now appears that variations in cDOM are in part responsible for the earlier reported inverse relationships between chlorophyll and SST. It has also been revealed that interannual chlorophyll trends linked to SST changes are predominantly attributable to physiological responses to changing ocean mixed layer conditions rather than phytoplankton biomass responses, which has profound implications with respect to primary productivity. The ability to simultaneously monitor phytoplankton chlorophyll and biomass has also provided a path for significantly improving photosynthesis models.

Despite these recent developments, heritage ocean color measurement wavebands were not selected to optimize the accuracy and diversity of spectral inversion algorithm products. New observations are needed to more accurately separate cDOM and pigment absorption as well as to characterize the spectral distribution of photosynthetic light absorption. These advanced characterizations will reduce uncertainties in ocean productivity estimates and the interpretation of temporal trends in ocean properties. Improved assessments of ocean plankton stocks (i.e., as carbon biomass) also require information on particle size distributions, which subsequently can improve understanding of carbon cycling within and below the surface sunlit layer. Furthermore, and as discussed above, characterizing the biological composition of ocean ecosystems and their changes can be equally important as quantifying stocks and rates. Thus, improved measurement capabilities are needed that support more detailed retrievals on ecosystem diversity than are currently possible with heritage measurement band sets. In a similar sense, understanding specific details on environmental stressors for phytoplankton production can be as important as detecting the presence of stress. For example, growth limitation by iron stress has a strikingly different impact on phytoplankton pigmentation than limitation by nitrogen or phosphorous. Observational capabilities that allow detection of specific primary stressors will thus improve interpretation of ecosystem behavior in response to changing physical environments.

A revolutionary advancement in global ocean ecosystem and carbon cycle science requires more than the advanced ocean color measurement capabilities discussed above. First, accurate satellite retrievals of ocean properties are dependent on accurate characterization of atmospheric properties. The oceans are a "dark target" compared to the atmosphere, and it is the latter of these that overwhelming dominates top-of-atmosphere radiances. Accordingly, improvements in atmospheric corrections will yield significant improvements in ocean products. Second, traditional ocean color measurements from low-earth orbit have fundamental limitations: they provide no information on ocean ecosystems at night, their detected signal is restricted to the uppermost layer of the surface ocean, they provide no information on the depth distribution of plankton properties, they are significantly compromised by clouds and aerosols, they yield no information on ocean ecosystems at high latitudes for large portions of the annual cycle, and a single sensor cannot resolve diurnal variability. Developing an observation strategy to address these issues is essential to the global ocean observing objectives of NASA's Ocean Biology and Biogeochemistry Program.

Next Steps

The following discussion presents various observational and modeling requirements that will improve understanding of ocean ecosystems. The proposed requirements will advance the spectral, temporal, and vertical sampling dimensions as well as include polar-orbiting and geostationary imaging spectrometers, space-based lidar, nanosensors, and a suite of observation and modeling systems.

In the 2007 Advanced Science Plan for NASA's Ocean Biology and Biogeochemistry Program, a next-generation global-observing ocean color sensor with hyperspectral capabilities from 350 – 800 nm plus near infrared and short-wave infrared atmospheric correction bands was rated as the highest priority future mission. This priority recommendation was addressed with the announcement of the PACE mission, as discussed above. This hyperspectral mission will allow us to evaluate ocean ecosystems and biodiversity beyond the current multi-band capabilities. Looking beyond PACE, we recommend that next generation ocean color missions be scoped to address problems along the coast and in wetland environments, in high latitude habitats, to assess the diurnal and day-to-day variability of stocks and rates, and to characterize the vertical distribution of organic matter in the upper layer of the ocean. These missions should be routinely paired with atmospheric sensors that provide information on aerosol type, atmospheric burden, and vertical distribution beyond what can be provided by the ocean color sensor alone.

Ever since CZCS began the modern satellite era of biological oceanography, ocean ecosystem studies based on ocean color data have been criticized for their inability to resolve plankton vertical structure beyond the top optical depth. This ‘unseen’ vertical variability causes significant errors in global assessments of plankton stocks and photic layer primary production. In addition, the vertical distribution of plankton and other biogeochemical properties is highly dynamic. As noted above, traditional low-Earth orbit ocean color sensors also provide no information on night-time ocean ecosystem properties and retrieval success is significantly reduced by clouds and aerosols. Active measurements of ocean ecosystem properties with a space-based lidar can provide new breakthroughs on all of the above-stated limitations. Lidar technology also allows profiling of plankton properties down to 2.5 to 3 optical depths, as well as active assessments of phytoplankton physiology and nutrient stress. Lidar can also provide a globally comprehensive data set for improving ocean color inversion algorithms and, when conducted with both UV and visible excitation wavelengths, can improve assessments of phytoplankton pigment and cDOM absorption. In addition, vertically resolved atmospheric properties measured by the lidar would improve the accuracy of atmospheric corrections for ocean color sensors.

Short time-scale variability in surface ocean ecosystem properties is challenging to resolve in a cost-effective manner with low-Earth orbit ocean color sensors. Nevertheless, these rapidly changing ecosystem properties provide important information on ecosystem functioning, including diurnal vertical plankton migration, primary productivity, cDOM photooxidation, phytoplankton physiology, and biomass growth and loss processes. Diurnally-resolved observations can also allow evaluation of how wind variability impacts upper ocean processes and mixed-layer depth, with associated influences on nutrient supply and particle dynamics. A capacity for repeated observations over the course of a day increases the likelihood of retrieving ocean ecosystems properties during conditions of scattered clouds, thus improving the 1-day resolution coverage over that achieved by a single low-Earth orbit sensor. Advanced ocean color sensors in geostationary orbit (GEO) can address the aforementioned limitations regarding temporal coverage of a low-Earth orbit (LEO) sensor. A global constellation of geostationary sensors would contribute improved spatial coverage of ocean color products in the tropics and subtropics, but not for high latitude/polar oceans. Alternatively, a constellation of lower cost miniaturized spaceborne sensors (e.g., CubeSats and NanoSats) with different equator crossing times could provide the desired diurnal coverage and would include high latitude/polar region coverage. Both LEO and GEO approaches have advantages and disadvantages with respect to global coverage, spatial resolution, and cost.

Remote sensing observations are a core component of NASA’s Ocean Biology and Biogeochemistry Program. They must be conducted at the highest quality level and sustained over time scales of decades to detect, quantify, and understand processes governing ocean ecosystems. However, remote sensing is not enough. Interpreting the changes observed from space and applying this understanding to forecasting and prediction of future change and improvements in ecosystem management requires parallel investments in ecosystem modeling capabilities. Advanced models are also needed to evaluate the implications of stock and rate changes at the remotely detected level of the plankton, assess carbon/energy transfer to higher trophic levels, and quantify export of carbon and other elements to depth. To accomplish the science objectives of the OBBP program, a strategy is needed to implement the merging of satellite data with in situ observing systems, mechanistic information from field process studies and laboratory experiments, and numerical model outputs.

Expected Accomplishments	Benefits for the Nation
• The assessment and modeling of global ocean ecosystems and their change in time and space. • Ability to predict biodiversity and its influences on the stability and persistence of ocean ecosystems. • Ability to assess different types of phytoplankton communities including harmful algal blooms. • Quantification of the links between ocean ecosystem function and diversity and environmental forcing factors.	•Global food security is dependent on oceanic and freshwater ecosystems that provide 20% of annual animal protein to 3 billion people each year. •Healthy ecosystems generate hundreds of millions of jobs in tourism, fishing, energy, and biotechnology. •Human health can be impacted by harmful algal blooms that require early detection and warning to coastal communities.

4.2 Life on the Edge

How are the diversity, function, and geographical distribution of aquatic boundary habitats changing?

The Challenge

The most productive and diverse aquatic habitats are found along boundaries. Air-water, land-water (e.g., coasts, lakes, estuaries and wetlands), seafloor-water, and ice-water interfaces are examples of boundary habitats in aquatic environments. They occur across temperature and salinity regimes from high latitudes to the tropics and around the world. They support complex biological communities, hosting integral parts of the life cycle of many aquatic and terrestrial species, including humans. Marine and freshwater boundary habitats provide substantial social, economic, and ecological benefits that have attracted humans to coastal zones across the Earth since the beginning of human history. Boundary habitats are also sites where important and active exchanges of carbon and other materials occur between different reservoirs. Examples include the delivery and transformations of carbon, nutrients, and pollutants from the land to the ocean through rivers, wetland tidal exchanges, the exchange of gases through the surface of the ocean, and the fixation and burial of some of these elements in wetland soils and marine sediments. Understanding and quantifying the impact of disturbance on these habitats is a requirement to defining optimal strategies to manage human activities that allow sustained use of the resources they offer. Indeed, such information is essential to address the UN Sustainable Development Goals (SDG; UN Resolution A/RES/70/1 of 25 September 2015) and specifically SDG 14[1] to "Conserve and sustainably use the oceans, seas and marine resources for sustainable development". *What is the role of biology in the*

[1]See UN Sustainable Goal Development Knowledge Platform, https://sustainabledevelopment.un.org/sdg14

accumulation, release, and capture of chemical elements on Earth in aquatic boundary habitats, and how, in turn, do these elements control the life cycles of different organisms?

Coastal, wetland, and ice boundary environments are of particular relevance to the ecology of the ocean and the ecosystem services they offer. For example, the global economic benefits of areas within 100 km of the coast represents over 60% of the world's total Gross National Product, or in excess of U.S.$26 trillion each year (Millennium Ecosystem Assessment, 2005a). Coastal wetlands alone, including tropical shallow-water coral reefs, seagrasses and other submerged macrophytes, mangrove forests, and saltmarshes provide benefits that exceed an estimated U.S.$15 trillion every year, yet they cover less than 10% of the Earth's land area (Millennium Ecosystem Assessment, 2005b). Wetlands are distributed globally and are located in settings as diverse as urban, rural, and remote locations. They serve as important nurseries for many aquatic invertebrates, fish, birds, turtle, and land species. They have important roles in the biogeochemical cycles of nutrients and carbon, in sediment accretion, and in the purification of fresh and salt water. Yet these areas are still poorly mapped globally.

Today there are still no tools to accurately measure status and trends in the biodiversity and health of global coastal areas, including nearshore waters, estuaries, beaches, and wetlands. A new satellite remote sensing strategy to cover this gap is required to revolutionize basic and applied ecological research of global coastal habitats and also of terrestrial habitats, enabling decisions that sustain ecosystem services including food provisioning and water security around the world.

Among the significant benefits that humans derive from coastal habitats is food. Coastal and brackish water fisheries and aquaculture are essential to the health and economies of many countries. Animal protein from fisheries and aquaculture accounts for over 40% of the total value of traded commodities in some island countries. Globally, these industries represent over 9% of total agricultural exports and 1 percent of world merchandise trade in value terms.

Aquaculture today provides nearly 50% of aquatic animal food for human consumption including fish food supply. In 2014, coastal aquaculture represented about 1/3 of global animal aquaculture, and estimated to be worth over U.S.$50 billion, nearly double the value estimated in 2008 (Bostock et al., 2010). The value is higher but not well documented when aquaculture of aquatic plants and algae is considered. The aquaculture of tropical seaweed species and of microalgae (e.g., *Spirulina*) is an expanding industry. Asia, and especially South-East Asia, have led aquaculture development since the middle of the 20th century, with China leading production and now accounting for nearly 60% of global aquaculture. However, aquaculture has exploded in all continents except for an apparent decline in Oceania (FAO, 2016). Global aquaculture is expected to continue to grow at a rate of about 5-7%.

Many coastal and fisheries-dependent communities are located in ecosystems that are already polluted and have suffered habitat degradation, overfishing, and the effects of other harmful practices, both inland and along the coast. Further, the aggregated global impacts of coastal fisheries and aquaculture on the marine environment are unknown and difficult to quantify with today's technology. These issues are at the core of the UN Sustainable Development Goals and "blue growth" initiatives. Management of human uses of coastal ecosystems requires timely and accurate information globally to ensure sustainable fisheries and aquaculture.

Aquatic habitats are sensitive to impacts from climate variability and human activities. In spite of their recognized value, they continue to be at risk from multiple factors, including sea level rise and urban, agriculture, and aquaculture development. Comprehensive assessments of the status and trends in the extent, biodiversity, and biogeochemistry of wetlands and coastal zones require development of new and unique synoptic observation strategies. We need basic tools, like maps of resources that can be updated regularly. Such maps help to visualize and quantify resource inventories, connectivity between habitats, and resource threats.

In extreme high latitude environments, the interaction between ice and water forms unique habitats. The edge of the ice pack is a dynamic zone that moves toward higher or lower latitudes depending on season. Melting ice in the spring can create stability in the water column that supports large blooms of phytoplankton. The timing, size, and type of ice edge algal blooms can define the success of a growth season and control recruitment of new members of invertebrate, fish, bird, and marine mammal populations. The composition of the food web in the Arctic Ocean and in the Southern Ocean near Antarctica depends on the seasonal extent of the ice-water boundary. These remote environments are difficult to explore by traditional means, yet their global and regional importance requires that we understand the impacts of extreme physical, chemical, and biological transitions in the ecology and ecosystem services associated with them. *In the face of projected human population increases, associated consumption of natural resources, and acceleration of environmental change, how can we best ensure the sustainable management of ecosystem services derived from these environments? What are the ecological and biogeochemical impacts of changes in aquatic boundary habitats, both locally and in the aggregate, on planet Earth?*

What We Know and Need to Learn About Boundary Habitats

Global ocean color missions have significantly advanced our understanding of the changing open ocean, by allowing advances in the study of near-surface phytoplankton and cDOM patterns. A criticism of global ocean color missions since CZCS is that we require tools with a combination of capabilities to address coastal and other boundary habitats. Specifically, these habitats are characterized by a high diversity of life living in diverse habitats that change rapidly and over short spatial scales. These 'unseen' dimensions of variability hinder global assessments of vigorous nutrient and carbon exchanges and monitoring of resources where they are used the most: in coastal and aquatic boundary regions of Earth. The current suite of ocean color and Landsat-class satellites has allowed us to conduct some assessments of a variety of boundary habitats. We have developed semi-analytical inversion models to identify optically-shallow habitats on the seafloor from hyperspectral imagery. Yet, successes realized using field spectrometry and airborne imagery have demonstrated the readiness of technologies to map seagrasses, coral reefs, kelp and other macroalgae, mangroves, and other important coastal habitats over larger scales. To characterize global ocean biological and biogeochemistry processes, this knowledge needs to translate now into space-based missions.

To date, research has provided only snapshots of boundary habitat ecosystems because the temporal, spatial, and spectral resolution of data is not sufficient to assess change over time. The phenology of different organisms is among the most sensitive of biological indicators of environmental change and ecosystem function, yet this phenology remains unresolved. In marine and freshwater coastal habitats, the connection between phenology, oceanography, and hydrology is close. Changes in one have direct implications on the other across diverse time and space scales, affecting individual organisms, habitats, and ecosystem functions. Similarly, our expanding use of coastal areas for aquaculture and various fisheries, for the extraction of sand and gravel, increasing tourism, and increasing discharges of various pollutants via rivers and coastal industrial operations have impacts that are as of yet uncharacterized and unmapped, and thus have unpredictable effects on our own health.

Ecosystem services depend on recurring or event-scale processes that control temperature, availability of water, light, nutrients, and the physical connectivity between habitats. Biological and biogeochemical processes depend on these drivers, including phytoplankton blooming; production and calcification in coral reefs; growth, leaf-out, and senescence in above-water vegetation; and reproduction and larval dispersal or adult migration patterns. The phasing of traits in the phenology of different organisms also influences the presence, absence, or relative abundance of species in an ecosystem. Disturbance can have effects on these variables that last for weeks to decades. *How do we study these changes, the processes that depend on them, and the processes that subsequently drive these changes?*

Many of the boundary areas are experiencing marked and persistent shifts in community composition, productivity, and biodiversity that ultimately affect the services these ecosystems provide to humanity. These shifts are the result of a changing environment, including changing climate and weather conditions, sea level, river inputs, and the rates of ice formation and persistence at high latitudes. For example, coral reefs and many other environments are affected by more frequent temperature extremes, ocean acidification, and changes in salinity. Many chronic and acute impacts are the direct result of human activities, such as degradation in water quality from industrial, agricultural, transportation, and residential pollution, or hydrologic alterations due to construction, urban development and changes in land use. These activities can have beneficial or negative effects on the many coastal resources that we depend on. *How can we quantify changes in aquatic boundary habitats at the appropriate scales in space and in time to allow effective management of the factors that control trends in critical ecosystem processes?*

Next Steps

The nominal spatial, temporal, and spectral resolutions of satellite-based ocean color sensors have limited the application of such observations to study or manage processes in boundary habitats. These Earth Observing sensors are typically flown in orbits designed to obtain coverage of the Earth's surface approximately every 3-days, which is adequate to observe only some boundary habitat processes. However, many ecological processes in coastal zones, including those that need to be observed as part of coastal resource monitoring, undergo faster changes, such as due to tides, floods, or events in the phenology of organisms. Also, the typical spatial resolution of 250 m to 1 km per pixel offered by global ocean color missions is at the high end of what is needed to resolve coastal, estuarine, delta, wetland, or coral reef areas around the world. This resolution is also not adequate to resolve the fractured nature of marginal sea ice zones in high latitude oceans.

While the Landsat and Sentinel-2 class of sensors offers global coverage every 5-16 days, these sensors are multispectral and typically feature broad spectral bands. They lack the higher signal to noise ratio required to detect changes in parts of the spectrum of coastal waters, and also lack a sunglint avoidance strategy. A new class of sensors now makes it possible to obtain multispectral images from around the globe at pixel resolution of less than 10 m, to as fine as 0.5 m or finer still. While these images provide an unprecedented view of land environments, their limited spectral and temporal resolutions, sensitivities and calibrations compromise their use for retrieving water - leaving radiances in aquatic environments. Moreover, the imagery in repeated samplings is typically collected at different view angles that may vary by > 30 degrees, which makes it difficult for comparing observations and is not considered optimal for assessing many features of aquatic ecosystems.

At present, there is no strategy that provides the combination of simultaneous medium to high spatial, spectral, and temporal resolution for observations and at the required radiometric quality and high signal to noise ratio. Such observations are required to observe phenology traits in marine and freshwater coastal habitats, as well as wetlands and other land cover. Observations at different scales are critical to understand the functional diversity of particular habitats, how different habitats may be connected into a larger regional ecosystem, and the impacts of change from regional to a global perspective.

A range of space-based polar and geostationary observations on large and small spaceborne platforms, airborne systems, and models need to be developed over the next decade to advance our understanding of boundary habitats. Foremost is the requirement to characterize coastal aquatic environments, shallow water benthic habitats, and high latitude boundary environments, including those affected by ice. High temporal resolution is necessary to resolve near-shore processes and characterize land-ocean exchanges, marginal ice zone processes, and the effect of tides, fronts, and eddies on marine life and biogeochemistry.

Despite its significance, even the bathymetry of coastal waters remains poorly known. Traditional methods are inadequate to study the great variety of coastal habitats over their large geographic extent. Water depth is a defining habitat factor of these complex three-dimensional environments, yet we only have accurate bathymetric charts for a small fraction of our nation's coastal waters. New potential exists for developing detailed bathymetric and benthic substrate maps for clear coastal waters from space-based and suborbital platforms by using a combination of very high spectral, spatial, and temporal imaging technologies combined with new active sensors, such as lidars.

High temporal-resolution measurements can improve assimilation of satellite data into operational models to improve assessment and management of coastal resources and to enhance ecological forecasting and predictions of the impacts of environmental change on aquatic and cryological boundary habitats.

A robust data processing and distribution infrastructure will be needed to support the large volume of data expected from such sensors. Developing an educated workforce—capable of designing scientific experiments and processing these advanced observations, and able to apply these technologies and products for monitoring—is also critical. Significant progress can be made by establishing effective links between research and decision-support tools for coastal managers and policy makers.

In addition to implementing strategies to obtain high quality temporal, spatial, and spectral resolution, observation of boundary habitats requires substantial advances in:

- Bio-optical algorithms that enable separation of constituents in Case-II waters, shallow waters, and in areas where different types of aquatic, wetland, or ice habitat are included within pixels or adjacent pixels.
- Improved atmospheric correction strategies to address with significant amounts of reflectance from the water and variable atmospheric constituents (e.g., absorbing aerosols and trace gases)
- Close coordination with field monitoring programs that can provide ground-truth time-series observations.
- Advances in ecological theory, including impacts of interactions between organisms and ecosystem valuation studies that link social and natural sciences.
- Integrated modeling and assimilation of multidisciplinary data to explain processes.

Expected Accomplishments	**Benefits for the Nation**
• Monitor coastal habitats for sustainable use of living and non-living resources. • Evaluate coastal and ice habitats for impacts of pollution (nutrients, hydrocarbons) and other impacts of anthropogenic pressures. • Assess impacts of climate change on coastal and wetland habitats. • Develop a practical classification for coastal habitats and the valuation of ecosystem services. • Assess carbon and nutrient cycling and sequestration in coastal habitats. • Identify hot-spots of habitat diversity for use in setting priorities for restoration and conservation.	• Creation and maintenance of jobs through blue growth and a blue economy. • Understanding the role of coastal habitats in human health and well-being. • Assessing impacts of inland nutrient, sediment, and pollutant inputs on coastal zones. • Improved forecasting of impacts and response of marine life and habitats to disturbance. • Creation of decision-making tools for ecosystem-based management, sustainable resource use, conservation and restoration. • Support of tourism and coastal management and ports operations.

4.3 Ocean Biogeochemistry and the Earth System

How do carbon and other elements transition into, between and out of ocean pools? What are the quantitative links between ocean biogeochemical cycles and climate?

The Challenge

The geological record demonstrates that ocean biogeochemical cycles are dynamic and persist in a delicate balance with climate, while the global ocean has experienced dramatically different geochemical regimes. The massive emissions of carbon dioxide due to fossil fuel burning over the last 200 years, coastal pollution, and retreating sea ice cover and glaciers at high latitudes have altered the chemical consistency of the present ocean, making it less alkaline (lower pH) and less oxygenated. In this and many other ways, humans are profoundly impacting the marine systems and altering the quality of our living environment. It is vital that we quantify and can predict how different biogeochemical cycles function in the ocean. To do so, we need an integrated observational-modeling framework that illuminates aspects of these cycles not only at the surface, but in the subsurface ocean which remains uncertain or unknown.

About half of the carbon emitted into the atmosphere by fossil fuels enters the ocean through solubility-driven gas exchange into ocean waters. Most of this carbon is exported to the deep ocean by the overturning circulation wherein cold, high latitude waters with high carbon concentrations sink to depth. On top of this large "solubility pump", carbon is also taken up by phytoplankton during photosynthesis. As phytoplankton are grazed and die, they sink and carry organic carbon to the deeper ocean in a process called "biological pump". This 'exported carbon' is slowly converted to inorganic forms and sequestered from contact with the atmosphere for 100s to 1000s of years. The carbon cycle is intimately linked with the elemental cycles of other chemical constituents, such as nitrogen, oxygen, phosphorus, calcium, sulfur, silicon and trace metals (e.g., iron, manganese, cadmium, aluminum). These elemental cycles constrain the metabolic processes of living organisms in the ocean and thereby affect the carbon cycle itself. Time-series analyses have established that ocean biogeochemical cycles are not at steady state, contrary to assumptions held as truth for nearly 100 years, and are therefore likely driving changes in marine community structure and composition.

Elemental cycles are controlled by different physical and biological processes, such as atmospheric deposition and exchanges across the coastal zone, the ice and the atmospheric boundaries, ocean circulation, and biologically-mediated export to the deep ocean. For example, distributions of nitrogen in the ocean are controlled by the competing effects of nitrogen fixation by cyanobacteria and diatoms at the surface as well as denitrification and remineralization at depth. Similarly, distributions of dissolved iron are determined by the balance between the supply mechanisms (e.g., from dust deposition, coastal and shallow sediment as well as sea-ice and hydrothermal sources) and removal mechanisms (e.g., uptake and recycling by phytoplankton at the surface, remineralization, and scavenging at depth). *How can we determine the fluxes of elements through key biological and physical processes?*

The surface ocean also contributes significantly to the global emissions of trace gases, such as the greenhouse gases carbon dioxide (CO_2), carbon monoxide, nitrogen oxides, and methane. Surface ocean biology releases dimethylsulfide, volatile and non-volatile organic sea spray, and other marine biogenic aerosols that act as condensation nuclei for cloud formation, thereby also affecting Earth's climate. At the same time, fixation of nitrogen, carbon, and oxygen by ocean biology and deposition of trace elements (e.g., iron, manganese, aluminum) carried by dust or ship emissions are important processes that change the ocean's biogeochemical makeup. *How can we monitor dust emissions and pathways over the global ocean? How do the mechanisms of air-sea gas exchange and aerosol emissions change with climate change?*

Ocean circulation is a fundamental control on biogeochemical processes from the planetary to the submesoscale. At the planetary scale, the global overturning circulation exposes deep waters to the atmosphere and is a fundamental constraint on the uptake of transient tracers, such as anthropogenic CO_2. Similarly, the ocean's natural carbon inventory and other biogeochemical properties, such as the distributions of nutrients and oxygen in interior waters, are sensitive to the structure and rate of the global overturning circulation. Smaller scale processes structure the upper ocean environment where planktonic organisms live and compete for resources. At the basin scale, for instance, wind-driven upwelling and downwelling patterns regulate variation in the mean vertical supply of nutrients to the euphotic zone, thereby controlling surface productivity patterns. These regions exhibit diverse and largely undocumented changes under climate change, both in magnitude and even in its sign (positive or negative). At shorter scales, mesoscale eddies produce transient vertical fluxes of nutrients into or out of the euphotic zone, depending on region. Submesoscale flows are associated with strong vertical velocities that enable rapid transport of living biomass into the ocean interior. *Can we couple observations with models to better quantify the influence of circulation at different spatial scales on biogeochemical cycling?*

Ocean biogeochemistry involves diverse interactions between physical, chemical, and biological mechanisms. Resultant elemental cycles are fundamental determinants of the character of the marine environment and have played a role in driving natural climatic fluctuations over geologic time. These cycles are also profoundly sensitive to climate, leading to the potential for dramatic future changes in the structure and function of the marine environment. The capacity to predict future behavior relies on a mechanistic understanding that, in turn, requires comprehensive observations of key constituents and rate processes. *How can we quantify the linkages between ocean biogeochemical cycles and microbial foodwebs? How do we characterize the role of these linkages on the Earth System and the quality of future environments? How do carbon and other elements transition into, between, and out of ocean pools, and how do we constrain the uncertainties in the cycling of carbon and other elements?*

What We Know and Need to Learn About Ocean Elemental Cycles

In many respects, NASA's ocean color missions provided the single greatest advance in biological oceanography during the 20th century. By viewing the oceans from space, we now estimate ocean productivity as being roughly equal to terrestrial net production, although uncertainties around both estimates remain large (>30% at a minimum). Ocean color data have also improved our understanding of carbon cycling in coastal zones and over continental margins, allowed the first global quantification of colored dissolved organic matter, and documented global ocean responses to El Niño-Southern Oscillation cycles.

The biological pump varies on scales from days to months to millennia and is the pathway by which atmospheric CO_2 is captured by ocean biology at the ocean surface and sequestered at depth. Because ocean biota utilizes elements such as oxygen, nitrogen, silicon, phosphorus, iron, and others for its growth and functioning, the biological pump plays an important role in the transport and redistribution of these elements as well. The vertical export and burial of carbon, nitrogen, phosphorus, silicate, and other elements within continental margins is an order of magnitude or two higher than in the open ocean, due to the shallow environment, high seasonal fluxes of terrestrial and estuarine particles and nutrients, and high marine productivity. However, much more data and research are needed to constrain the fluxes that control the biological pump at various temporal and spatial scales.

The past few decades have also witnessed significant advances in ocean biogeochemical models. The cutting-edge models consist of expressions governing transformation rates as a function of environmental variables. These expressions yield prognostic source/sink terms that are coupled to three-dimensional, general circulation models and provide representations of ocean dynamics and tracer transport. Notably, the horizontal resolution of the general circulation models determines the scales of motion that can be explicitly resolved. Recent models now include plankton functional types that are separated on the basis of ecological or biogeochemical functions. This approach leads to a reasonable approximation of the impact of community composition on elemental cycles and transfer rates. Such models can be interrogated to provide information on the mechanisms controlling phytoplankton distributions, including the proximal factors limiting growth and the impacts of climate variability and change.

Earth System Models tend to suggest that oceanic primary productivity will decline under future climate warming, weakening the biological pump of carbon to depth and potentially reducing the net supply of energy to marine ecosystems. However, different models produce substantially different predictions with respect to how large these reductions will be. Confidence in model predictions can be only as high as the underlying mechanistic understanding that is used to develop model formulations and as good as their balance between their higher process complexity, on one hand, and their lower spatial resolution, on the other. Thus, more data are required to validate the simulated rates and fluxes, so that accuracy and uncertainty in model predictions continue to increase and decrease, respectively. As the diversity of observed variables increases, the constraints on model behaviors must be improved.

Next Steps

Quantifying, monitoring, and predicting changes in ocean elemental cycles and their interactions with atmospheric, terrestrial, and cryological systems requires information on stock sizes and key transformation rates. Advanced ocean remote sensing missions can provide vital observations in this context, particularly given the capacity of space-based platforms to deliver a synoptic view of processes globally. In the development of the current Advanced Science Plan, we have assumed that PACE will succeed and a series of follow-on missions will contribute an equivalent set of measurements.

To capture the highly dynamic nature of ocean biogeochemical cycles, advanced ocean color sensors in geostationary orbit are needed, as already indicated. The 2007 Advanced Science Plan recommended geostationary hyperspectral radiometers to capture the temporal dynamics of ocean physical, biological, and biogeochemical processes of ocean ecosystems (including boundary habitats) and to capture transient events occurring during ocean hazards and disasters. This recommendation continues to be valid. Briefly, geostationary sensors provide much improved spatial coverage on sub-daily to annual time scales and improved global spatial coverage when deployed as a constellation of sensors. Furthermore, substantial improvements in modeling ocean productivity can be realized by coupling temporally resolved measurements form geostationary platforms with both regionally-targeted high spatial and spectral measurements of surface properties and global day/night lidar measurements of vertical distributions in ocean particle abundances, size distributions, and phytoplankton functional types and physiology. Smaller space-borne platforms may also help maintain the long-term data record of ocean color and derived properties past the currently proposed and authorized missions by fostering the development of more flexible, faster, and less expensive approaches, such as nano- and cube-type satellites already being explored by the academic and private sectors, with support from and in collaboration with NASA.

In situ autonomous observational platforms are also required, as these provide critical information about three-dimensional structure, high-frequency temporal evolution, and variables not accessible from remote platforms. There is also a role for suborbital platforms that can perform high resolution mapping of upper ocean properties with hyperspectral or lidar-based instruments and provide access to high-precision observations of atmospheric composition that reflect oceanic processes on large scales.

Finally, numerical modeling will continue to be invaluable as a means of synthesizing observational understanding, testing hypotheses, and developing future projections of biogeochemical cycles on seasonal to centennial time scales. Numerical models can help us take apart the elemental cycles in the ocean and evaluate processes that are critical, or more uncertain, or expected to change most in future climates. However, models need to include coastal, ice, and riverine outflow processes and thus require much higher resolution than the presently nominal 1-degree grid cell size as well as modeling techniques, such as nested or closure parameterizations.

Expected Accomplishments	**Benefits for the Nation**
• Quantification and trends in ocean carbon pools and primary production. • Assessment of elemental transfer rates between pools and export from the surface photic zone. • Characterization of plant growth constraints, responses to episodic events, and potential implications of future nutrient budgets. • Assessment of links between alterations in the physical ocean environment and the pools and fluxes of key elements. • Provision of specific remote sensing products central to the development of advanced ocean circulation-ecosystem prognostic models.	•Understanding how the ocean's food webs are changing and predicting future changes allow for better management of marine food resources. • Better assessment of atmospheric chemistry and pollution. • Evaluation of man-made nitrogen sources to the coastal ocean that impact marine organisms and water quality. • Impact of changing agricultural practices that alter dust and iron delivery, essential for ocean ecosystems. • Improved assessments of carbon pools and fluxes, including estimation of allowable emissions, credits, and trades.

4.4 Transient Threats and Disasters

How can knowledge of the spatial extent, dispersion, intensity, and frequency of transient hazards and natural disasters in the aquatic environment improve forecasting and mitigation?

The Challenge

Every year, disasters threaten natural environments and human communities around the word. Life, property, and commerce along the coast and in inland waters are vulnerable to the formidable forces of nature and to threats from accidents or other human-caused problems. Hurricanes, tsunamis, harmful algal and bacterial blooms, and oil spills represent just a few of the transient threats to aquatic ecosystems and the services they provide. Such intermittent threats can occur over time scales of hours. They require immediate responses to mitigate their impacts. In many cases the initial event may be followed by additional problems as a result of the initial stress. *The overarching challenge is to provide useful, accurate products on the time and space scales that are appropriate for early warnings, emergency response efforts, and decision makers.*

To date, environmental hazard monitoring has primarily focused on land-based hazards, such as volcanoes, droughts, floods, landslides, and fires, and their impacts on land surfaces. Natural hazards, however, have tremendous impacts on the world's marine, estuarine, and freshwater ecosystems, the communities residing along these water bodies, and the economies they support. For example, recent years have witnessed record-breaking events impacting coastal zones and costing billions of dollars. Large-scale and infrequent events like hurricanes and tsunamis alter seascapes, coastlines, and the adjacent landscape. They impact water quality and biodiversity, devastate habitats, and greatly impact organisms and associated food webs. They often affect human communities adjacent to these water bodies and show rely on clean water supplies. *Can remote sensing observations be used to help monitor large weather events and resulting impacts such as flooding and associated floating debris and pollution?*

Phytoplankton and bacteria can grow and accumulate rapidly in dense, visible patches near the surface of the water. Some of these 'blooming' species produce potent neurotoxins that can be transferred through the food web and adversely impact higher forms of life, such as zooplankton, shellfish, fish, birds, marine mammals and humans. The mechanisms producing such harmful blooms are not easy to predict. Monitoring is warranted to protect human and other ecosystem communities from these toxins in the water they drink, foods they eat and the air they breathe. However, false positives are common in forecasting programs. These mistakes can be costly, as they result in unnecessary emergency responses or unwarranted applications of regulation that, for example, result in unnecessary closures of fisheries or beach access. *How can we improve harmful algal and bacteria bloom detection, monitoring, and forecasting?*

Petroleum and other hydrocarbon products are essential to modern society and must be transported considerable distances over land and sea. Ten to fifteen transfers are typically involved in moving oil from the oil field to the final consumer. Many of these transfers occur on ships or through pipelines on the seabed. In addition to transportation accidents, oil spills can result from controlled releases by shipping operators and from oil production platforms. Marine oil spills can be dispersed over large distances by wind, waves, and currents within a few hours and can severely impact organisms ranging from microscopic phytoplankton to marine birds and mammals. Impacts on offshore, sea ice and coastal ecosystems, habitats, and biodiversity can range from short-term changes to long-term damages. The livelihood of residents of coastal communities is impacted by oil spills, particularly those based on fishing and tourism. *How can the composition, extent, and depth of oil spills be detected rapidly and tracked over hourly time scales on the water surface and underwater?*

What We Know and Need to Learn about Hazards and the Coastal Zone

Progress has been made in evaluating impacts and threats from hazards, but the field is still in its infancy and there is considerable room for improvement. Each threat or hazard has its own set of observational requirements that must be addressed. However, the following event properties represent a generalized set of characteristics that need to be quantified to evaluate aquatic hazards:

1) The spatial extent of impact area and the fracturing of habitat;
2) The dispersion or movement of the hazard;
3) The intensity, severity or classification of the hazard;
4) The frequency and potential predictability of the hazard;
5) The communities, habitats, or ecosystems most impacted, including humans.

Remote sensing tools can be used, at least partially, to assess each of these hazard properties, but appropriate data latency and spatial and temporal resolutions are needed to optimize their utility for communities and responders.

<u>Spatial extent.</u> The spatial extent of a hazard varies according to the type of event. Hurricanes and tsunamis are generally of large spatial scale and can cover 10 to 100's of km. However, the spatial extent of flooding, plumes of suspended materials and pollutants, and damage to habitats often requires observations at 1-30 m resolution. Harmful algal and bacteria blooms, and oil spills, can be small localized patches or cover 100's of kilometers. Assessing concentrations or distribution, plumes, and dispersion trajectories can require observations at <30 m resolution. In addition, cloud cover can be a major limiting factor in providing immediate imagery of a threat or disaster.

<u>Movement or Dispersion.</u> The time scale at which information about pending threats and hazards is needed is generally on the order of hours, with repeat coverage required on hourly and daily timescales, depending on the location and speed of the event. Remote sensing observations can be assimilated into biophysical models of circulation to compensate for gaps in cloud cover and provide forecasts of areas most likely impacted by the threat or disaster.

<u>Severity.</u> The severity or intensity of a threat is generally a physical quantity, such as the amount of oil or toxins within or floating on the water. In the case of oil spills, both the thickness of the oil slick and the type of oil spilled are critical to cleanup efforts. Hurricane intensity is based on storm size and sustained wind speeds and impacts include the extent of flooding and amount of debris and suspended matter in the water column. Better methods are required to distinguish the optical fingerprints of various pollutants and suspended matter. Improvements in accuracy of harmful algal

and bacteria bloom warning systems are warranted across the different bloom types and associated impacts.

Impacted communities/ecosystems. The ability to have prior knowledge of a shoreline is invaluable for assessing damage and providing mitigation strategies for threats. Such knowledge includes maps of bathymetry that are seamless from water to land and maps of the location and density of different types of aquatic habitats. In the case of spills, for example, berms can be set up to protect the most vulnerable habitats and organisms. Historical data can be archived to identify the ecosystems most likely to be impacted by various natural and human-made threats and used to develop adaptive sampling strategies. Aquatic habitat maps, however, are often inadequate or outdated. For example, the location of much of the world's submerged aquatic vegetation in coastal waters is not known and such maps would require periodic updates.

A comprehensive program focused on aquatic hazard detection may need to be developed to locate available archived imagery, maps and field data, as well as concurrent NASA and other relevant observational and modeling tools. Such a program could interface with responders to coordinate how these many aspects of detection and monitoring can aid communities across the nation.

Next Steps

Quantifying the extent and impacts of aquatic hazards and natural disasters requires higher temporal, spatial, and spectral resolution imagery than currently available from most satellite platforms and of sufficient radiometric and geometric quality so that scientific questions can be addressed. In some cases, the most useful deployment strategies for local threats would be airborne or underwater sensors on either manned or autonomous vehicles that can be routinely deployed with a suite of different types of passive and active sensors over an impacted area. Airborne sensors may, in theory, be flown beneath clouds, although many challenges remain for producing quality imagery beneath cloud-covered skies. Assessing immediate threats to high latitude and remote regions is likely best served with satellite assets, due to challenges in operations associated with airborne and underwater campaigns. Active sensors that can penetrate clouds may also be warranted for providing time-series measurements and improving forecasting. For autonomous, regularly-timed assessments, satellite-based remote sensing remains an irreplaceable tool for local observations. The combination of portable spaceborne, airborne, and underwater technologies provides the capability to deploy powerful and effective observation strategies quickly, including in areas not otherwise accessible.

In addition to new sensors and platforms, the following issues must also be addressed:

- Rapid-assessment and processing of imagery that can be used without ancillary data or imagery that are not immediately available (i.e., operational processing).

- New and improved algorithms are needed that are not merely site-specific empirical regressions, but instead can accurately determine the quantity and composition of floating and suspended material and chemicals across diverse aquatic environments. This advancement will likely require spectral libraries of constituents of interest.

- Improved atmospheric correction approaches must be developed to deal with significant amounts of near-infrared reflectance and highly variable atmospheric constituents (e.g., absorbing aerosols and trace gases) common over inland and coastal regions and potentially correlated with particular hazards (e.g., dust, precipitation, ice clouds, etc.). This advancement will require concomitant field data of known targets within the imagery to validate the processing.

● Integrated modeling and data assimilation will be required to tie together in situ measurements and diverse remote sensing data, such as sea surface temperature, vector winds, bathymetry, sea ice extent and delineation of fronts and other surface phenomena (e.g., using Synthetic Aperture Radar) into biophysical models. Expanded model testing to different regimes would be necessary to improve skill for future predictions.

Expected Accomplishments	**Benefits for the Nation**
• Identification of potential natural hazards affecting marine life and human communities. • Integrated modeling and data assimilation efforts to provide more accurate and timely forecasts of hazards. • Quantification of short- and long-term physical and biological responses to hazards in coastal waters. • Assessment of current algorithms and development of new approaches to remotely derive biogeochemical parameters in response to hazards in the ocean environment.	•Improved forecasting of acute and chronic natural and anthropogenic hazards, including large storms, tsunamis, toxic spills, and icebergs that impact human life and property. • Provide critical knowledge needed for planning appropriate coastal development, design of nearshore structures to withstand wave and tidal surge, and improved disaster preparedness in coastal communities. • Improved understanding of how natural hazards impact and shape our coasts.

5 OBSERVATIONAL STRATEGIES

The four core Science Questions encompass the foremost issues in ocean biology and biogeochemistry research within NASA's Ocean Biology and Biogeochemistry scientific research program. Below we document the observational requirements for each question, many of which overlap multiple questions. For example, substantial progress can be made toward answering all four science questions by expanding the spectral range and wavelength resolution of global water leaving radiance measurements. These new data will allow separation of ecosystem components key to addressing all four science questions. Similarly, enhanced spatial (10 to 100 m^2) and temporal (sub-daily) resolution will contribute important information to answering these four science questions. Such overlaps allow the diversity of new measurement requirements to be consolidated into a tractable suite of four specific Observational Strategies and ancillary field and modeling observation for the required data:

5.1 Global Satellite Light-detection And Ranging (LIDAR)
5.2 Geostationary Imaging Spectrometer
5.3 Combined high spatial, high spectral, high temporal, high signal to noise (*H4*) observations
5.4 Portable sensors on orbit and suborbital, including assets on or in the water

These recommended observational strategies would complement long-term, high quality, global ocean color data records from polar-orbiting Low-Earth Orbit satellite sensors, such as MODIS, VIIRS, and the more advanced PACE. As highlighted in Section 3.0, maintaining time-series of sufficient length, consistency and continuity to quantify uncertainty and determine climate variability and change on ocean biological and biogeochemical processes globally is a research priority for the OBB Program. Section 3 also pointed out the importance of maintaining an operational capability to measure ocean color such as that provided by the Visible Infrared Imaging Radiometer Suite (VIIRS) on the JPSS series of satellites. However, the Global Ocean Observing System is designing specifications for an ocean color Essential Ocean Variable (EOV) to address societal needs in a sustained manner. This requires the ability to derive phytoplankton diversity, abundance, and physiological state over the global ocean, including coastal zones. VIIRS is not designed to measure the fluorescence of phytoplankton stimulated by the sun, the subtle differences in color between phytoplankton groups, or to distinguish between living phytoplankton, detritus and colored dissolved organic matter, which are characteristic of coastal zones. To reach this new threshold in addressing the ecology of the global ocean, NASA has designed the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Mission with new and advanced spectral and radiometric specifications. NASA is planning for the launch of the PACE Mission in the 2022 timeframe.

Each observational technology in the section below is formatted to provide the following information:

1. Science questions
2. Platforms
3. Sensors
4. Technology Needs
5. Ancillary Requirements

5.1 GLOBAL SATELLITE LIGHT-DETECTION AND RANGING (LIDAR)

1. Questions

A central focus in global ecosystem remote sensing has been the characterization of photosynthetic communities. These terrestrial and aquatic 'plants' constitute the primary conduit through which inorganic carbon is converted to organic matter, which in turn fuels the global food webs that feed humanity and creates biological pathways for carbon sequestration. Understanding responses of primary producers to climate variations is thus of foremost science and applications importance. For marine ecosystems, knowledge of phytoplankton stocks (in carbon units, not chlorophyll) and net primary production (NPP) is fundamental to understanding climate impacts on marine ecosystems. While major advances have been made with heritage ocean color sensors in quantifying phytoplankton biomass and NPP, large uncertainties in these assessments remain. However, it is foreseeable that major reductions in these uncertainties can be achieved in the next decade with targeted remote sensing investment.

It has been widely recognized since the original CZCS mission that the inability of passive ocean color measurements to resolve phytoplankton vertical structure is a primary source of error in global phytoplankton biomass and productivity assessments (Platt & Sathyendranath, 1988). This vertical biomass structure has long been documented in the field and is particularly strong in the climate-sensitive, high-latitude regions (IOCCG, 2015; Babin et al., 2016). Global measurements of phytoplankton vertical structure at sub-monthly resolution can be achieved with depth-resolving satellite lidar measurements (Behrenfeld et al., 2013). It has also been recognized since CZCS that passive ocean color measurements are restricted at high latitudes due to persistent fog and cloud cover, periods of polar night, and prevailing low solar elevations (IOCCG, 2015; Babin et al., 2016). For these reasons, ocean color data are completely absent over extensive areas of the polar seas for many consecutive months each year, which severely limits our understanding of how these systems are responding to environmental change. Again, lidar measurements can address this issue by providing measurements between clouds, through significant fog and cloud cover, and at all times of the year (measurements are made both day and night) (Figure 2). Thus, satellite lidar measurements can revolutionize our understanding of global phytoplankton stocks by quantifying biomass throughout the annual cycle in high latitudes and by retrieving the vertical structure in global plankton communities that is hidden from passive ocean color sensors.

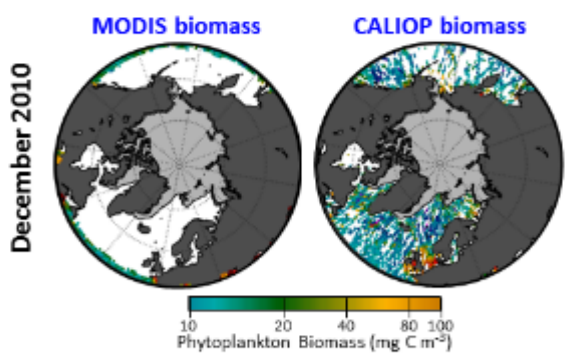

Figure 2: Phytoplankton biomass observations from (left) MODIS and (right) CALIOP poleward of 45°N (white = no data) for December 2010 . Gray shading = ice cover.

In summary, a global-observing, ocean-focused satellite lidar will allow major advances toward answering the questions:

1) What are the global stocks of phytoplankton and total particulate material in the photic zone and how do they vary in space and time?

2) How are phytoplankton populations and total particulate material vertically distributed through the water column and how are these distributions linked to physical processes?
3) How do polar plankton populations vary during the full annual cycle and how is this variability linked to climate forcings?
4) How do specific nutrient stressors influence phytoplankton stocks and net primary production?

2. Platform

Lidar measurements of ocean plankton properties (including vertical structure and physiological properties) have been routinely conducted from airborne platforms for decades. The ability to retrieve global plankton surface-layer biomass from a space-based lidar has also been demonstrated using CALIOP data (Behrenfeld et al., 2013) and the CALIOP orbit has been demonstrated to effectively capture complete annual cycles of phytoplankton biomass in polar regions (Behrenfeld et al., 2016). For a new ocean-focused lidar mission, a noon sun-synchronous orbit similar to that of CALIOP (Figure 3) is recommended, which gives a 16-day repeat cycle. In contrast to CALIOP, it is recommended that the new lidar mission platform have an orbit altitude of ~400 km, as this lower orbit will allow better water column penetration from current high Technology Readiness Levels (TRL) laser technology.

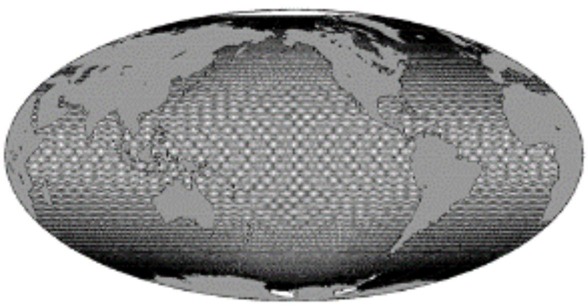

Figure 3: 16-day orbit repeat tracks for the CALIOP sensor.

3. Sensor

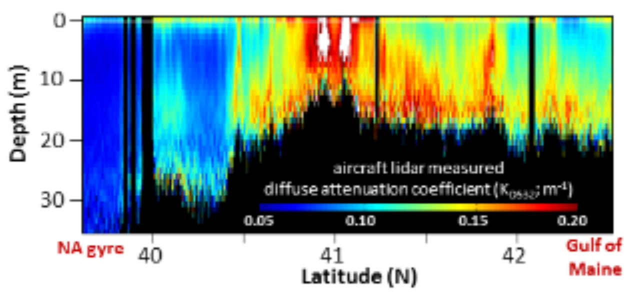

Figure 4: Vertically-resolved ocean retrievals from an airborne HSRL. Example is for the diffuse attenuation coefficient (Kd) measured along a flight track from the Gulf of Maine (right) to the North Atlantic (NA) Gyre. Data are from the 2014 NASA Ship-Aircraf Bio-Optical Research (SABOR) experiment. Black = no data due to a cloud under the aircraft or a depth below lidar detection (~3.0 optical depths).

Ocean color-based global assessments of water-column-integrated net primary production (ENPP) suffer from three major sources of uncertainty: (1) vertical structure in phytoplankton biomass, (2) separation of phytoplankton pigment and colored dissolved organic matter (cDOM) contributions to light absorption, and (3) physiological variability. Errors in ENPP from phytoplankton vertical structure are dominated by subsurface features above ~3 optical depths. This is because the very low light intensities at greater depths minimize the influence of biomass features below ~3 optical depths. Fortuitously, a satellite lidar built with current technology can retrieve plankton vertical structure properties at meter-scale resolution to between 2.5 and 3.0 optical depths (Figure 4). In addition, a satellite lidar with near-UV and visible emission wavelengths would allow quantification of phytoplankton and cDOM absorption coefficients. Finally, a satellite lidar with chlorophyll fluorescence detection capabilities can provide new information on phytoplankton physiological variability associated with conditions of iron- and light-stress (Behrenfeld et al., 2006; Behrenfeld & Milligan, 2013).

While the CALIOP sensor has proven useful for 'proof-of-concept' demonstrations of ocean retrievals from a satellite lidar, CALIOP cannot satisfy the aforementioned science objectives of characterizing photic layer phytoplankton stocks, assessing physiological properties, or reducing errors in global ocean NPP estimates. To achieve these goals, an advanced sensor is needed that includes polarized and depolarized channels similar to CALIOP and has the following additional characteristics:

1) Measurement capabilities that enable independent separation of attenuation and backscattering in the retrieved signal
2) Meter-scale vertical resolution of measured signal
3) Laser emissions NIR, VIS, and near-UV wavelengths
4) Measurement bands corresponding to emission wavelengths, plus a chlorophyll fluorescence band

The first of these requirements is absolutely critical. Launching another basic lidar similar to CALIOP would provide limited advancement in ocean science. Such a lidar measures attenuated backscatter and depolarization from the atmosphere and ocean, but does not allow the direct separation of the scattering and attenuation components. For previous applications of CALIOP data, this issue was 'worked around' by assuming an empirical relationship or employing simultaneous data from MODIS. Both of these approaches are unsatisfactory and result in large errors in retrieved ocean properties. One solution to this problem is provided by the High Spectral Resolution Lidar technique (HSRL). An HSRL lidar separates particulate and molecular signals by employing an additional filtered channel. This addition enables direct, independent and calibrated measurements of particulate backscatter and extinction separately, and improves the specification of particulate depolarization as well. An HSRL has not yet been flown in space. However, meter-scale vertical plankton profiling with an airborne HSRL has been extensively demonstrated in the field (Azores 2012, SABOR, NAAMES) (Figure 4). With respect to requirements 3 and 4 above, lidar technology has been recently advanced to include a near UV emission wavelength (TRL 6 expected in 2017) and lidar measurements of chlorophyll fluorescence have been already demonstrated (Hoge et al., 2005). Thus, no significant technological developments are necessary for a satellite lidar capable of achieving the measurement requirements identified here. It is easily foreseeable that such a lidar mission could be flown in a 'virtual constellation' with the PACE mission. Here, 'virtual' means at a different altitude (~400 km) from PACE (~650 km). This virtual constellation ensures that lidar measurements are collected at the full range of viewing angles of the PACE ocean color sensor and that the maximum scientific benefits are realized from the lidar (e.g., depth penetration). With the two orbits noted above, the average temporal coincidence would be ~20 minutes (which is short relative to the typical time scale of variability in subsurface plankton profile features), with the distribution of coincidence times normally distributed around this average.

In summary, the recommended measurement capabilities for an advanced satellite ocean lidar sensor are:

1) Lidar emission in near-UV (e.g., 355 nm), visible (e.g., 532 nm) and NIR (e.g., 1064 nm)
2) 5 km along-track spatial resolution of derived properties, with surface pulse width of ~100 m and pulse-to-pulse separation of ~300 m
3) Measurement approach allowing direct separation of absorption and scattering components of retrieved signal (e.g., HSRL technique)
4) 2 to 3 meter vertical resolution of subsurface derived ocean properties, requiring a measurement vertical resolution of ≤ 1 m

5) Polarized and depolarized measurement bands corresponding to emissions wavelength, plus a chlorophyll fluorescence detection band.
6) Day and night observations during all months with a minimum mission lifetime of 2 years and goal mission life of 10 years

4. Technology Needs

A 2-wavelength (532, 1064 nm) HSRL-type lidar has ample field demonstration from airborne platforms to be immediately ready for extension to a space-based sensor. An HSRL-type lidar with the additional UV-band (355 nm) is in development and expected to reach TRL 6 in 2017. Investments to accelerate this development time-line would ensure space readiness for an ocean lidar mission flown in virtual formation with PACE. Continued advancement of detector technology would also benefit the ocean lidar mission by improving realized signal to noise (SNR), allowing deeper signal detection, and improving along-track resolution of retrieved properties.

5. Ancillary requirements

Measurements from an ocean-optimized satellite lidar will provide an unprecedented advancement in our understanding of global ocean ecosystems and biogeochemistry. However, as described in Section 4, the vision offered in this Advanced Science Plan is for a lidar as one element in the broader observational framework. Specifically, passive ocean color data from NASA's upcoming PACE mission will provide continuous global fields of phytoplankton surface biomass and physiology. As with all ocean color measurements, PACE observations will be severely limited for climate-sensitive, high latitude regions and they provide no information on phytoplankton vertical structure. Parallel measurements with the satellite lidar described herein can address these shortcomings of PACE by providing a global sampling of vertical structure in biomass and physiology. Lidar measurements, though, do not achieve the continuous horizontal coverage of PACE data, nor do they penetrate to the bottom of the photic layer. The third element in this observational infrastructure would be a global array of autonomous profiling floats equipped with optical and geochemical sensors. This array of profiling floats can extend the satellite observations to the bottom of the photic layer and into the mesopelagic zone, and can provide biogeochemically-relevant measurements unavailable from space. However, even at a density equivalent to today's ARGO physical float array, this new BioGeoARGO array cannot achieve the spatial coverage of the satellite sensors. By recognizing the strengths of each approach, a coordinated infrastructure of all three technologies can be envisioned (Figure 5) where measurements from each provide critical ancillary information for the other two approaches.

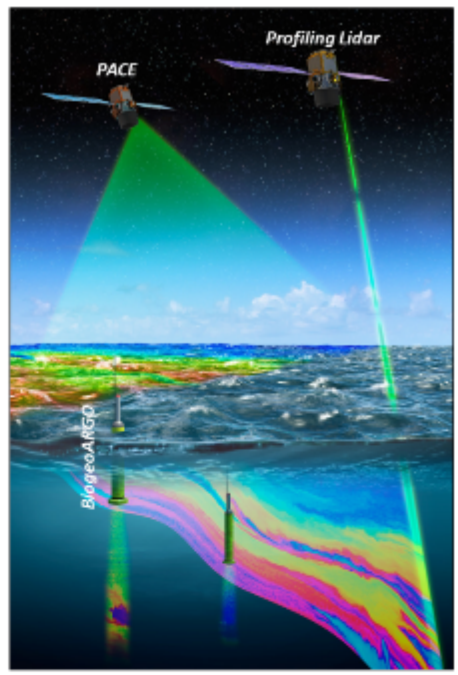

Figure 5: Artistic rendition of observational infrastructure foreseeable in the coming decade where PACE, an ocean profiling satellite lidar, and an array of in situ profiling BioGeoARGO float measurements allow a 3-dimensional reconstruction of ocean.

5.2 Geostationary Imaging Spectroradiometer

1. Questions

While current space-based, sun-synchronous polar orbiting assets have helped to elucidate the broader temporal and spatial scales of key ocean processes, they are inadequate—due to their limited temporal coverage frequency—to constrain physical, ecological and biogeochemical fluxes and rates as well as the variability in biogeochemical stocks within the marine environment. For example, recent studies have strongly suggested the importance of meso- and sub-mesoscale events to annual carbon budgets and phytoplankton populations (e.g., Claustre et al., 1994; Lévy et al., 2012; Mahadevan et al., 2012; Omand et al., 2015). Both high temporal and high spatial resolution capabilities are required to study frequent but ephemeral sub-mesoscale events. Moreover, the lack of space-borne capability to observe phytoplankton growth and population changes at their natural time and space scales is one of the reasons for the high uncertainty in global NPP. The diurnal cycle of solar irradiance engenders physical and biogeochemical responses within the surface layer of the ocean requiring diurnal observations to reduce uncertainties in primary production and other measurements.

Despite comprising a modest areal extent of the global ocean, continental margins contribute a disproportionately greater share of global net primary production (15-20%), biological pump transfer of carbon to seabed (~50-70%), carbon sequestration through burial, net air-sea transfer of carbon dioxide, and lateral exchange of carbon, nutrients and contaminants to the open ocean. While we have estimates for some of these processes and fluxes, our knowledge of the transformations and fates of materials within coastal environments remains in its early stages. Nowhere more so than coastal regions are the combined effects of long-term climate change and human population growth most acute. Intensifying pressures on coastal ecosystems have given rise to more frequent and expansive harmful algal blooms detrimental to fisheries and human health, hypoxic waters and ocean acidification that kill or harm marine organisms, pollution events such as oil spills, adaptations of phytoplankton physiology, growth, and species composition that affect global biogeochemical cycles and provoke unknown feedbacks in the climate system.

With a space-borne capability to measure ocean color at high-frequency (<2 hours) and half-kilometer spatial scales, we could quantify the rates of biological and biogeochemical processes including primary production, track inventories of biogeochemical constituents in time and space, and examine the impacts of physical processes such as upwelling, fronts, eddies, filaments, mesoscale and sub-mesoscale processes, surface currents and tides—even sea ice edge processes if the position were just right—on the distribution, production, consumption, and fluxes of ocean constituents (IOCCG 2012; Mouw et al. 2015).

The top-level science questions that a geostationary ocean color mission will address include:

> *(1) How are the productivity and biodiversity of ocean ecosystems changing, and how do these changes relate to natural and anthropogenic forcing, including local to regional impacts of climate variability?*
>
> *(2) How do short-term coastal and open ocean processes interact with and influence larger scale physical, biogeochemical and ecosystem dynamics?*

(3) How are variations in exchanges across the land-ocean interface related to changes within the watershed, and how do such exchanges influence coastal and open ocean biogeochemistry and ecosystem dynamics?

(4) How do airborne-derived fluxes from precipitation, fog and episodic events such as fires, dust storms and volcanoes significantly affect the ecology and biogeochemistry of coastal and open ocean ecosystems?

(5) How do episodic hazards, contaminant loadings, and alterations of habitats impact coastal ecosystem health and services?

2. Platforms

This capability is focused primarily on Geostationary (GEO) orbit, but other complementary orbits capable of high-frequency diurnal observations are also mentioned at the end of this section.

Geostationary orbit

GEO offers unprecedented and virtually continuous temporal coverage of the Earth's surface that has been the cornerstone for tracking and forecasting weather patterns from space since 1960. Meteorological satellites such as NOAA's GOES, EUMETSAT's SEVIRI and JMA's Himawari 8 collect earth observations every 30, 15 and 10 minutes, respectively. NOAA's GOES-R will collect full-disk imagery of the western hemisphere every 15 minutes. Such high frequency measurements are essential for capturing atmospheric processes as well as daily variations in sea-surface temperature. Much of the temporal and small-scale variability of ocean ecosystems remains elusive in ocean color

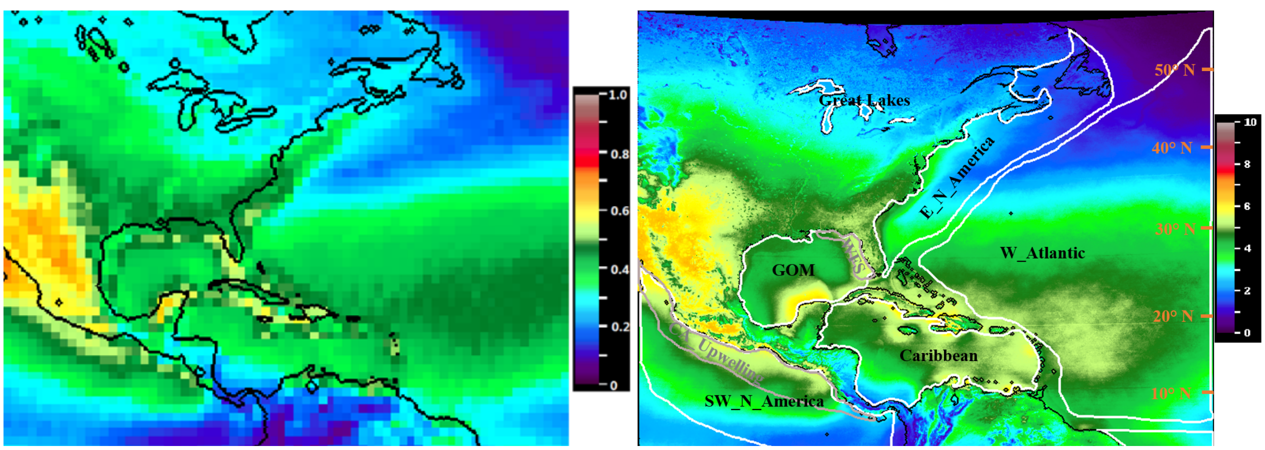

Figure 6: Mean proportion of cloud-free observations during a day for a polar-orbiting sensor (Left panel) based on MODIS-Aqua observations between 2006 and 2011 and mean number of cloud-free hourly observations during each day from GOES East (75°W over the equator) (Right panel) for solar zenith angle < 80°, based on cloud cover data between 2006 and 2011. The higher spatial resolution of a Geo ocean color mission will confer a higher probability of cloud-free observations compared to GOES 4km (~20%) and MODIS 1km (~10%). Nominal location for GEO-CAPE (95°W) is annotated on the right figure. (from Feng et al. 2016 in review).

imagery from sun-synchronous polar orbiting sensors such as SeaWiFS and MODIS. Cloud cover reduces the number of ocean color observations from polar orbiters over an ocean region to only a few measurements per week at best (Figure 6). A geostationary sensor can obtain on average about 10 times more hourly clear-sky images per day than a once per day clear-sky image from a single polar orbiting sensor (Feng et al., 2016). "Polar-orbiting instruments study the effects of processes, whereas the geostationary Instruments can study the process itself" (Chesters, 1998). GEO observations can provide the temporal frequency required to quantify diurnal rate processes and stocks for the open ocean and highly dynamic coastal environments. Furthermore, geostationary ocean color spectroradiometers will provide the temporal frequency, spatial resolution and spectral depth necessary to detect and track hazards such as HABs and oil spills, enabling managers to mitigate their impacts.

Leveraging geostationary observations from international partners could produce quasi-global ocean color products. The Korean GOCI-II sensor has a scheduled launch date of March 2019 and will provide observations from the eastern Indian Ocean across the western Pacific (Figure). A team at the French space agency, CNES (Centre National d'Etudes Spatiales), has matured a mission called GeOCAPI (Geostationary Ocean Color Advanced Permanent Imager) that would image much of the Atlantic Ocean, coastal seas and portions of the western Indian Ocean (Figure 8). The Indian Space

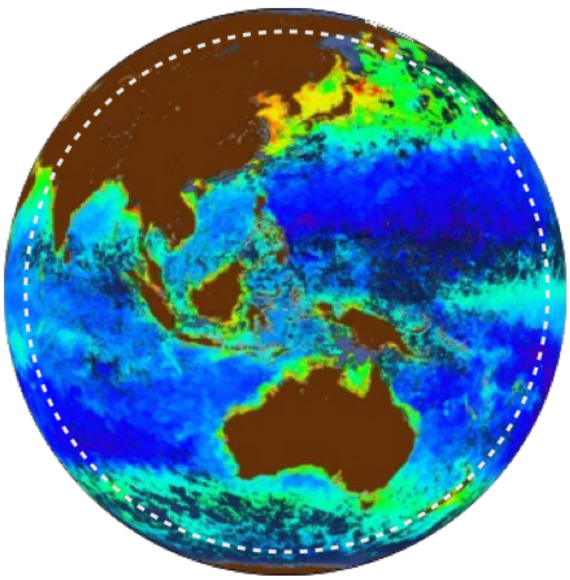

Figure 7: Ocean Color usable field of view for the Korean GOCI-II sensor, which is scheduled to launch in March 2019.

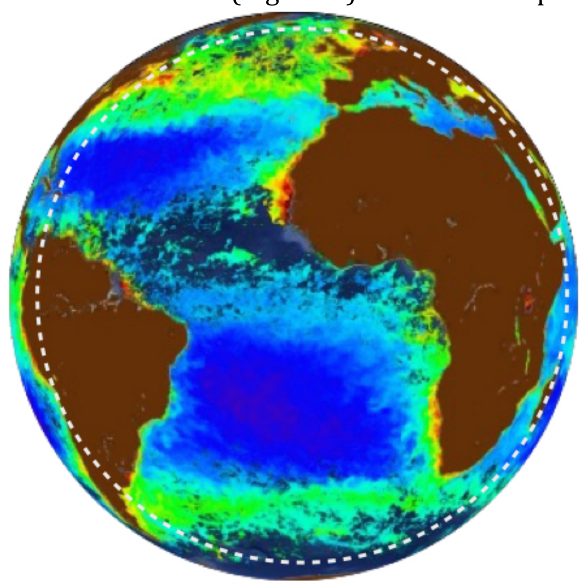

Figure 8: Planned European GeOCAPI ocean color sensor usable field of view. Proposal for GeOCAPI was submitted to ESA in May 2016.

Research Organization (ISRO) is planning a hyperspectral Vis-NIR ocean color sensor as part of the geostationary imaging satellite (GISAT), which would image primarily the Indian Ocean (IOCCG, 2012). A single U.S. geostationary sensor along with GOCI-II, GEO-OCAPI and GISAT would complete a global constellation of geostationary ocean color sensors.

A U.S. sensor at ~94° to 98° W would be capable of collecting high frequency observations from the eastern Pacific Ocean to the western Atlantic Ocean including coastal waters along North and South America and the Laurentian Great Lakes (Fig. 9). Two geostationary ocean color sensors in orbit at similar locations as the GOES-East and GOES-West platforms (~135° W and 75°W) would be ideal to meet the full breadth of measurement requirements including bi-hourly observations in the open ocean and coastal ocean (Figure 9) over major portions of both the Atlantic and Pacific basins. Hosting GEO ocean color sensors as secondary payloads on commercial or government satellites will significantly reduce the cost, since accommodation costs and hosting fees would be far less than for dedicated spacecrafts and launch vehicles (Fishman et al., 2012). Furthermore, commercial GEO satellites are designed to provide reliable operations for a typical 15-year lifetime, comparable to the actual lifetimes of current polar-orbiting spacecrafts Terra and Aqua. The extent of useful ocean color observations extends up to ±50-60° north, south, east and west from nadir and is dependent upon view angle and solar zenith angle, which determine the air mass fraction. PACE and sensors like those on Sentinel 3 and GCOM-C would provide high frequency sub-diurnal coverage of polar regions to complete a global integrated constellation of ocean color observations.

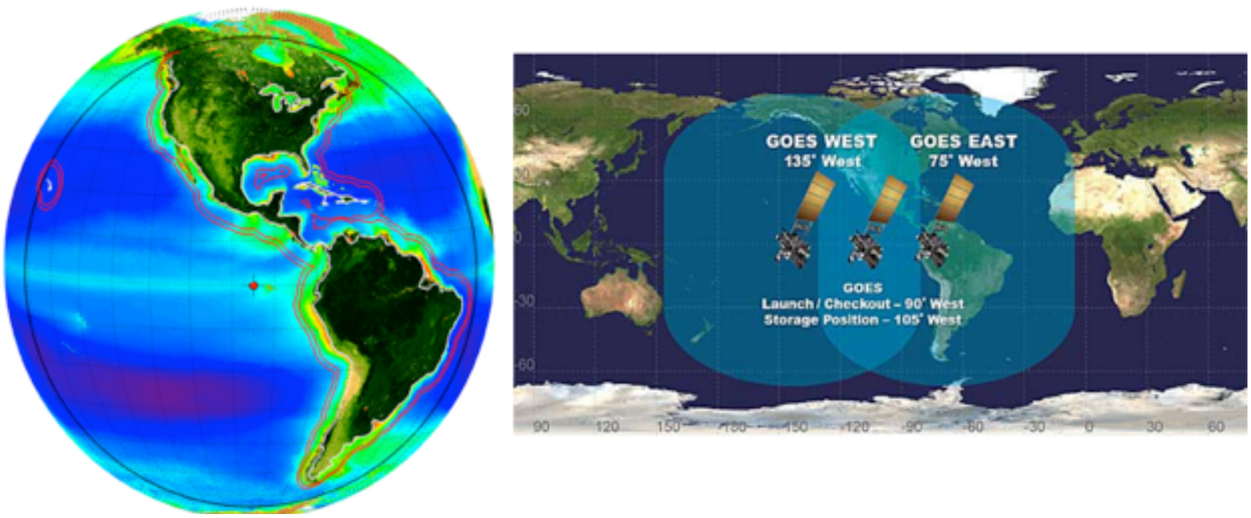

Figure 7: (left) Ocean color field of regard (black outer line; ~67° sensor view angle) for a satellite in geostationary orbit at 95°W. (right) NOAA GOES (Geostationary Operational Environmental Satellites) satellite location and coverage for GOES-East and –West platforms (image from http://goes-r.gov/mission/history.html).

Complementary Orbits Capable of High-Frequency Diurnal Observations

Other orbits provide unique capabilities that are complementary rather than alternative for geostationary missions. A satellite location at Lagrange Point 1 (L1; e.g., DSCOVR mission) permits continuous coverage of the sunlit portions of the earth throughout each day. Thus, complete diurnal coverage of the earth would be possible. The angular views from L1 are too extreme for ocean color retrievals in waters surrounding the northern polar regions. Satellites within a Molniya orbit could provide diurnal observations of high latitude regions for 11-12 hrs per day. The challenge with such missions is the higher costs associated with the instrument (large aperture and telescope for L1) and mission (spacecraft and launch for both orbit types).

3. Sensors

The South Korean Geostationary Ocean Color Imager (GOCI), which launched in 2010, is the first and only ocean color sensor to have flown in geostationary orbit. It has demonstrated the feasibility and utility of geostationary ocean color observations. The instrument is a 2D step-and-stare filter radiometer with an 8-band filter wheel, a ~360 m nadir GSD, conducts eight hourly scans per day over a 2500 x 2500 km local region surrounding the Korean peninsula (Lee et al., 2011; Oh et al., 2011), and achieved higher SNR than SeaWiFS (Hu et al., 2012). The solid performance (Ahn et al., 2015) and modest cost of GOCI have prompted the Korea Aerospace Research Institute (KARI) and the Korea Institute of Ocean Science and Technology (KIOST) to develop a 13-band follow-on sensor with Airbus Defense Systems called GOCI-II, which will launch in March 2019. Other improvements in GOCI-II include a local GSD of 300 m over Korea (~250 m at nadir) and full-disk imaging capability (1 km GSD). The NASA Ocean Biology Processing Group (OBPG) is collaborating with the GOCI team from the Korea Ocean Satellite Center to improve GOCI data products. OBPG (through the Ocean Biology Distributed Data Active Archive Center) is now distributing hourly GOCI L1b products and standard NASA L2 products to advance the maturity and application of geostationary ocean color measurements.

Over the past 7 years, the NASA GEO-CAPE Ocean Science Working Group has developed the science objectives as well as measurement and instrument requirements for a principally coastal, ocean color GEO mission (Fishman et al., 2012; NASA GEO-CAPE, 2015). Those spectral and sensitivity requirements are comparable to those proposed and justified by the NASA PACE Science Definition Team Report for the planned polar-orbiting PACE Ocean Color Instrument (NASA 2012). Not surprisingly, the requirements proposed in this document are consistent with both sets of recommendations (Table 1).

Table 1: Required measurement capabilities to accomplish the stated science objectives for a geostationary ocean color mission.

	Minimum	**Goal**
Temporal Frequency (within 70º solar zenith angle)		
Open Ocean	≤3 hours (3x/day)	≤2 hours (5x/day)
Coastal	≤2 hours (5x/day)	≤1 hour (10x/day)
Spatial Resolution (ground sample distance at nadir)		
Open Ocean	1000 m	500 m
Coastal	350 m	200 m
Spectral Range	350-900 nm; 1250 and 1615 nm	340-1050; 1615 and 2260 nm
Spectral Resolution/Bandwidth (FWHM)		
UV-Vis	≤15 nm[a]	≤5 nm[b]
NIR	15 to 40 nm	10 to 40 nm
SWIR	30 and 75 nm	75 nm
400-450 nm (NO_2)	NA	≤0.75 nm
Spectral Sampling		
UV-Vis	None	≤2 nm[b]
NIR	None	≤5 nm
SWIR	None	None
400-450 nm (NO_2)	None	≤0.25 nm
Spectral Bands	≥25 multi-spectral bands[c]	Hyperspectral UV-Vis-NIR
SNR (based on typical top-of-atmosphere radiances within 70º solar zenith angle for 15 nm or 10 nm bandwidths for UV-Vis and specified ground sample distance)	300 (at 350 nm) 1000 (360-720 nm) 600 (720-900 nm) 250 for 1250 nm 200 for 1615 nm	500 (<360 nm) 1500 (360-720 nm) 800 (720-1050 nm) 300 for 1615 nm 200 for 2260 nm

Geostationary Orbit Location	94° W ±2°	135°W & 75°W ±2° (two sensors: ~GOES-E and –W)
Science Coverage (extent of coverage at the edges of the field-of-view will vary with season due to the impact of solar zenith angle on the air mass fraction)	~67° sensor view angle (up to air mass fraction of 5) ~60° N to 60° S ~160° W to 30° W	~67° sensor view angle (up to air mass fraction of 5) ~60° N to 60° S 145° E to 7.5° W
Uncertainties in Ocean Reflectance (by wavelength) <400 nm 400-600 nm 600-750 nm	 ≤20% ≤5% ≤10%	 ≤10% ≤3% ≤5%
Uncertainties in Geophysical variables	≤25%	≤15%
Ancillary Data	Total Column O_3 Total Column NO_2	Total Column O_3 Total Column NO_2

[a] Bands for chlorophyll-a fluorescence line height should be 10 nm wide (665, 678 and 748 nm bands).

[b] Near urban areas with variable tropospheric NO_2, it would be beneficial to retrieve total column NO_2, which would require a bandwidth of ≤0.8 nm and spectral sampling of ≤0.4 nm.

[c] Nominal band centers equivalent to those identified in Appendix II of the PACE SDT Report (2012).

Instrument design studies supported by the NASA GEO-CAPE mission pre-formulation activity have suggested three viable classes of scanning instruments for meeting geostationary ocean color observations; they include: (1) 2D step-and-stare filter wheel radiometers (e.g., GOCI), (2) wide-angle pushbroom spectrometers and (3) multi-slit pushbroom spectrometers. The costs for these nominal sensor concepts were estimated by the Goddard Space Flight Center Instrument Design Lab and ranged from ~$100 million to $200 million (NASA GEO-CAPE, 2015). An airborne simulator for a geostationary ocean color multi-slit pushbroom spectrometer (Multi-slit Optimized Spectrometer; MOS) has flown on multiple field campaigns in 2015 and 2016. Wide-angle pushbroom spectrometers for geostationary air quality missions (NASA TEMPO, Korean GEMS, European Sentinel 4) are being fabricated for near-term launches. Furthermore, an ocean color hyperspectral UV-Vis-NIR-SWIR wide-angle spectrometer was recently proposed to NASA Earth Venture Instrument-4 solicitation. Hence, all three instrument classes are technologically mature.

4. Technology Needs

There are no technological limitations to implementing ocean color sensors in GEO (NASA GEO-CAPE 2015). Existing or planned atmospheric sensors in geostationary orbit would help mitigate the challenge of obtaining improved characterization of aerosols and trace gases for proper retrieval of time-varying ocean color observations. Current capabilities allow for spatial resolution and image stabilization for a nadir ground sample distance (GSD) of ~200 m. However, GSD increases with sensor viewing angle yielding a spatial resolution of ~400 m near the edge of the sensor field-of-view where data quality is still useful. While a nadir GSD of 500 m to 1 km will suffice for the open ocean, a higher spatial resolution on the order of ~250 m GSD is preferred for estuaries and coastal ocean regions.

5. Ancillary Requirements

The diurnal and spatial variability of aerosols, ozone (O_3), and water vapor within the coastal domain will require nearly coincident satellite retrievals of these constituents. Aerosol properties and water vapor can be retrieved by a geostationary ocean color sensor with requirements specified (Table GEO-1). Total column O_3 measurements from the GOES-R Advanced Baseline Imager will become available in 2017 and extend through the next two decades from the GOES-S and –T satellite series. Daily measurements of atmospheric total column nitrogen dioxide (NO_2) are also necessary (Ahmad et al., 2007) with coincident diurnal data needed near major urban areas such as the northeastern U.S. and southern California. Daily measurements of NO_2 will be available from the TROPOspheric Monitoring Instrument on the European Space Agency's Sentinel 5 missions and potentially diurnal measurements from NASA's EVI-1 Tropospheric Emissions Monitoring of Pollution (TEMPO) mission and a ground-based network of instruments (Tzortziou et al., 2014).

5.3 COMBINED HIGH SPATIAL, HIGH SPECTRAL, HIGH TEMPORAL, HIGH SIGNAL TO NOISE (*H4*) OBSERVATIONS

1. Questions

Coastal marine, wetland, and freshwater habitats of the world are critical for the well-being of humanity. Yet today we still don't have the tools needed to make the systematic observations of these habitats around the world to address fundamental science questions, establish baselines of biodiversity and habitat integrity, evaluate their extent and health, and measure change over time. Establishing baselines in these variables and measuring changes are fundamental to managing our coastal zone. This is at the top of priorities identified by the international community, as established in the U.N. Sustainable Development Goals (including SDG 14), the Ramsar Convention, Convention on Biological Diversity (CBD) and other agreements. The need for global biodiversity monitoring has been recognized by the Group on Earth Observations (GEO) and by the Intergovernmental Oceanographic Commission (IOC; Lindstrom et al., 2012).

Field measurements can be very detailed and of very high quality, and are necessary to obtain high-quality, detailed observations of critical variables. At issue, however, is that traditional field surveys and monitoring programs are limited in geographic scope, in sampling frequency, and in the ability to quantify biological and habitat diversity. Overcoming these limitations requires remote sensing using satellites in space (Muller-Karger et al., 2014; Paganini et al., 2016; Strauch et al., 2016). Remote sensing and traditional field surveys combined provide the framework for repeated, high-quality synoptic observations required to detect change across regional and global scales. These observations provide the basis to monitor the Essential Biodiversity Variables (EBV, Pereira et al., 2013) needed to address the goals of national programs and international treaties as mentioned above. Such EBVs are defined by programs like the Marine Biodiversity Observation Network (MBON; Duffy et al., 2013; Muller-Karger et al., 2014) of the Group on Earth Observations Biodiversity Observation Network (GEO BON; Pereira et al., 2013).

Here we outline the fundamental characteristics of the next generation Earth observing missions necessary to characterize and monitor coastal marine, wetland, and freshwater resources. This requires a combination of platforms and sensors that provide simultaneous medium to high spatial resolution, high spectral resolution, and high temporal resolution observations, with high radiometric quality and signal to noise ratios. We refer to this observational strategy as *H4* remote sensing. New technology exists today that would enable collection of science-quality *H4* satellite observations of coastal habitats and wetlands around the world, but a process to move such sensors to launch has not been formalized.

H4 sensing is specifically intended to address these questions:

1) *What are the diversity and structure, abundance, and spatial distribution of coastal marine, freshwater, and wetland biological communities around the globe?*
2) *How are these habitats and communities changing?*
1) *What is the role of boundary habitats and communities of organisms living in them in the accumulation, release, and capture of chemical elements, locally and in global budgets, and in turn, how do these elements control the life cycles of different organisms?*
2) *How do we ensure the sustainable management, sustainable use, and conservation of coastal and wetland ecosystem services?*

2. Platform

Satellite platforms provide a bird's eye view of the Earth's coastal aquatic and wetland habitats. They enable repeated regional and global observations that complement the measurements collected on the ground. The choice of orbit is also critical in defining the temporal resolution for the coastal observing mission, and to define the type of telescope, scanning strategy, etc.

A coastal habitat monitoring mission needs to collect observations from pole to pole. It needs to track rapidly changing populations and environmental conditions at time scales of hours to days. It requires a strategy to address cloud cover, which is expected to interfere with roughly 50% of observations (Mercury et al., 2012). It also needs to optimize aquatic reflectance measurements by sampling near noon, through a minimum of atmosphere, while minimizing sunglint contamination of the measurements. While aquatic measurements may be collected within a range of viewing angles (typically ±45°), observations of emergent wetland vegetation requires repeat observations using fixed viewing geometries to properly interpret observations, ideally off-nadir to minimize the contaminating effects of water reflections observed through the canopy (Turpie et al., 2015).

<u>Orbit</u>: Sun-synchronous Low-Earth orbit (500-900 km).

<u>Temporal resolution</u>: Possible solutions to achieve a revisit time of near-daily to several times per week include one or several small, agile, satellite platforms that can point precisely with accurate knowledge. For example, a single, agile *H4* satellite in a 3-day repeat orbit cycle, with field-of-view dimensions of 30-100 kilometers and a ground sample distance of 30 m, could accommodate observations of several hundred coastal habitats every day by consistently acquiring data using both along-track pointing for glint mitigation as well as cross-track targeting (Osterman et al., 2016). Global *H4* mapping is desired because such information is useful to monitor coastal habitats impacted by human and global-scale pressures across the world. Global *H4* coverage with one sensor is not possible, as this requires sacrificing one of the *H*'s. Scaling *H4* to meet the objective of weekly or better comprehensive global coverage requires flying a multi-satellite mission, which would provide both greater geographic coverage and offer repeat observations at sub-tidal frequencies, at different times of the day.

Additional platform requirements: The platform motion could help increase signal to noise ratios by scanning aquatic targets slower than land or wetland targets (e.g. Osterman et al., 2016). The platform should have minimal jitter or other stability problems.

There should be a strategy for sustained calibration including frequent observations of the moon and ground validation efforts. It needs to be capable of on board storage of high volume spectrometry data, and provide frequent downlink opportunities to bring the observations to the ground.

3. Sensor

The coastal habitat sensor(s) should be designed to work in tandem with the platform to achieve the mission goal of addressing the science and applications questions.

The Landsat, Sentinel-2, and SPOT missions define a class of observations that have allowed us to track changes in land use and land cover since the early 1970s. They provide the historical context of global multispectral observations at medium (10 to 60 m) spatial resolution with which to conduct additional targeted observations of coastal aquatic and wetland habitats. The spectral signature of phytoplankton and other particulate matter, dissolved colored materials, bottom reflectance, and land cover are typically confounded in multispectral data such as that of Landsat and Sentinel-2, and in coarser (> 30 m) spatial resolution data [IOCCG, 2000; Dekker et al., 2011; Hestir et al., 2012; Hestir et al., 2008; Goodman & Ustin, 2007]. An *H4* mission should overcome these limitations but take advantage of the continuing operation of Landsat and Sentinel-2(a and b) missions. It should complement these observations with additional sampling dimensions to observe changes in biodiversity at spatial scales relevant to resource use.

This leads to the following general spatial, spectral, temporal, and radiometric requirements.

Spatial: The *H4* mission should collect observations at a spatial resolution of ~30 m (Turpie et al., 2015). This augments the ongoing Landsat and Sentinel-2 missions.

Spectral: The sensor or sensors should collect observations with sufficient spectral resolution and radiometric sensitivity to measure the spectral features of different components of land and water environments. This requires continuous coverage at ~5 nm resolution in the VNIR between about 340 nm and 900 nm, and ~10 nm between 900 and 2125 nm. Alternately, SWIR bands at 1240 nm and 2125 nm should be available for atmospheric correction.

The spectral resolution will enable detailed spectrometry observations, experimental algorithm development, and synthetic reconstruction of the bands recommended by the PACE Science Definition Team (PACE SDT, 2012) and the bands of other sensors (e.g. Osterman et al., 2016). This is required to separate constituents in the visible band, and conduct observations of particular fluorescence phenomena. Spectral regions of interest include chlorophyll-a absorption at 435-438nm and 660nm; pigment absorption features between 550 and 900nm, chlorophyll-a and other pigment fluorescence, and sediment, and oxygen concentration signals. The atmospheric correction strategy, including spectral bands, will be critical in the coastal zone.

An important case study has been conducted in conjunction with the HyspIRI mission proposed by the 2007 Decadal Survey. HyspIRI is prescribed to provide spectrometry observations at 30 m resolution with a radiometric sensitivity specified for land observations and a revisit time of 19 days.

Radiometric: The aquatic *H4* sensor signal to noise (SNR) requirements will drive instrument aperture, telescope, and spectrometer throughput and detector sensitivity. The SNR requirements for an ocean color instrument are outlined by the International Ocean Color Coordinating Group (IOCCG) and the PACE Science Definition Team [IOCCG 2013, PACE SDT 2012]. As mentioned above, SNR may be increased by slow-scanning aquatic targets by mounting a sensor on an agile platform, but it can also be accomplished with a gimbaled sensor. Polarization sensitivity of the sensor should be much lower than 1% (and knowledge to <0.2%), for the reasons explained in the PACE SDT (2012). Other considerations include digitization at 12 to 14 bit resolution, detector saturation, linearity, response vs. view angle, and minimizing any instrument artifact contribution to measured radiance such as cross-talk and other stray light contamination.

4. Technology Needs

There are at present several airborne sensors and sensors flown on interplanetary and lunar missions that provide the technological basis to develop a family of *H4* sensors. Such technology is at TRL 7 or higher for Earth observations from space. The *H4* dimensions (high temporal, spatial, spectral, and radiometric) may be available separately, but an investment is required to evaluate trade-offs, sensor integration, and platform development to maximize the delivery of science-quality observations.

Accelerated investments in this technology would enhance the possibility to complement observations to augment the follow-on Landsat continuity missions, Sentinel-2, and the PACE missions. There need to be investments in studying on board data storage and processing, data compression for broadcasting, and ground system data processing, data curation and distribution systems.

Critical investments should target also the development of products that implement hyperspectral atmospheric correction and bio-optical algorithms for both aquatic and adjacent wetland habitats, including adjacency effect corrections.

5. Ancillary requirements

The *H4* observations of aquatic habitats will require the suite of ancillary observations collected routinely for global ocean color observations. Retrieval of aquatic radiometry from satellite radiometry uses ancillary data in addition to those observations collected by the sensor. For example, meteorological data (wind speed, surface atmospheric pressure, relative humidity), concentrations of atmospheric gases (water vapor, ozone, nitrogen dioxide), and sea ice data (cover, location) are needed.

Ancillary field data are highly desirable. These will help calibrate and validate the *H4* observations. Such data should be shared along with metadata such as described in the PACE SDT (2012).

5.4 PORTABLE SENSORS ON ORBIT AND SUBORBITAL, INCLUDING ASSETS ON OR IN THE WATER

1. Questions

Imagery with spatial resolution of meters or less is critical for mapping and tracking fine-scale features along coastal margins, including river plumes, flooded land regions, and seafloor features. Hazardous and episodic events require repeat sampling on the order of hours and not days or weeks, and require an imaging platform that can potentially be used under cloud cover. Inland lakes, rivers, and coastal estuaries are also difficult to monitor at spatial scales available from most ocean color sensors. The most effective approach for such applications is from portable sensors that can be mounted on spaceborne, airborne, and underwater platforms. The type of platform can determine the pixel resolution from smaller satellites and piloted aircraft at high elevations to remotely piloted airborne and underwater vehicles.

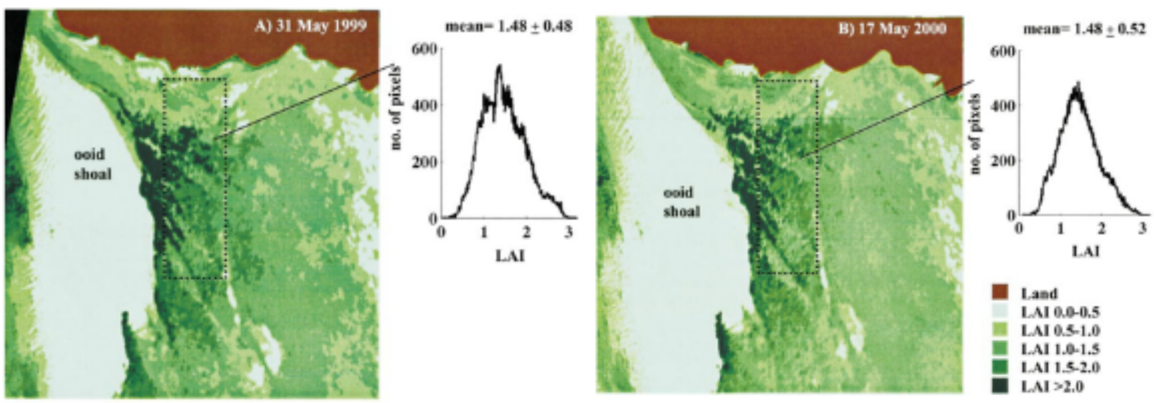

Figure 8: Adapted from Dierssen et al. (2003). Seagrass Leaf Area Index (LAI) modeled with PHILLS imagery before and after Hurricane Floyd, a category 4 storm with winds of 135 mph and gusts up to 190 mph, passed directly across this area on 14 September 1999. Although this storm inflicted significant damage to structures on neighboring Lee Stocking Island, the turtlegrass distributions in this relatively protected site were virtually undisturbed.

Portable sensors can be used to support weather forecasting, hazard and coastal water quality assessment, inland flooding, coastline topography mapping, and harbor and shipping lane management. Imaging spectrometers can also be used to track changes in benthic habitats and impacts from episodic events like storms (e.g., Fig. 10). Two different prototype sensors with demonstrated utility are coastal lidars and imaging spectroscopy. Portable coastal lidars are an important tool for mapping vertical and horizontal topographic features along the coastal zone at spatial resolutions far surpassing satellite-based measurements. These lidars can also differentiate seafloor properties in shallow water based on bottom brightness and spatial roughness.

From underwater vehicles, sensors have been used to image the seabed for a variety of applications including applications to habitat mapping, marine archaeology and for oil and gas exploration. Such mapping has usually been done with digital photography, but sensor technology has advanced towards the ability to obtain high spectral and spatial resolution, georeferenced, optically corrected digital underwater maps of different habitats, minerals, substrates, and organisms.

Within the water column, the opportunity of adapting the ARGO float array to contribute to the herein proposed science already exists; indeed, NASA OBB has helped to support the development of BioARGO or similar floats equipped with a variety of bio-optical sensors and the deployment of these platforms globally, though mostly in open ocean settings and even in sea-ice covered regions. Internal ocean structure will always be a limitation to remotely sensed observations. A profiling lidar will be limited to the upper ~3 optical depths at best (at most ~70 m). Coordination and collaboration with national and international, multi-year, autonomous biofloat profiling efforts will undoubtedly be useful for NASA OBB science and will complement spaceborne and airborne observations.

Top level science questions include:

1) *Can we provide timely information to decision makers on the spatial extent, dispersion, intensity, severity, and frequency of aquatic hazards that influence communities and ecosystems?*
2) *What are the fine-scale and potentially rapid changes in vulnerable and important aquatic habitats in optically shallow waters, including damage to or loss of coral reefs, seagrass meadows, mangroves, and kelp forests?*
3) *How can we better delineate the land-sea boundary of complex shorelines including the topography and bathymetry for advance planning of neighboring communities?*
4) *Can we map features on the deep-sea bed that have implications for ecosystem management and industry (mining, oil exploration, pipelines)?*

2. Platforms

Miniaturized Satellites: Over the past decade, miniaturized satellite platforms dubbed "nanosatellites" have been developed by academic and commercial entities to provide a lower cost alternative to traditionally deployed satellite missions. CubeSats, for example, are made up of roughly 1 liter cubic units that weigh no more than 1.33 kg per unit and are commonly constructed with commercial off-the-shelf (COTS) components for their electronics and structure. CubeSat systems are launched and deployed using a common deployment system which enables unification and quick exchanges of payloads and launch opportunities on short notice. These qualities make them uniquely suited for testing a variety of portable sensors, including innovative new technology that may be deemed too risky for a traditional missions. In recent years, NASA has worked to foster innovation in designing, building and delivering flight-qualified, small satellites. The expansion of technology into the small satellites realm has the potential to expand observational capabilities to address hazards and natural disasters in aquatic ecosystems, as well as other scientific questions.

Manned Aircraft: NASA has long been a leader in developing and deploying airborne remote sensing platforms. Airborne sensors can sample at fine spatial scales (1-10 m) and be deployed repeatedly throughout the day with nearly unlimited repeat coverage. Flight lines and scanning geometries can also be oriented to optimize retrievals (e.g., avoid sun glint) and their range can be greatly expanded by launching from ships. Different types of aircraft have been used depending on the science question. Overflights with a lower flying Twin Otter that can image at <1 m resolution to provide fine-scale analyses of coastal regions that can detect Langmuir cells (Dierssen et al., 2015) and resolve boundaries between different benthic types (Hedley et al. 2015). Pressurized aircraft that avail much higher altitude can provide 8-10 m pixel resolution and increase spatial coverage by more than an order of magnitude compared to twin otter. A larger sampling domain allows for resolution of regional-scale features related to sediment, phytoplankton growth and carbon flux in coastal ecosystems. Aircrafts provide a fairly stable platform which makes it easier to geocorrect, allow for instruments with considerable energy payloads, and have space to mount computers and sensors. Disadvantages of this type of platform include the considerable cost to maintain aircraft and flight team and the extended duration of field campaigns that must wait for appropriate environmental conditions (e.g., cloud and white-cap free, low swell).

<u>Remotely Piloted Aircraft Systems or Drones:</u> The advent of small unmanned drones for conducting aerial surveys has blossomed in the last few years. In addition to simple photography, drones have been adapted with higher instrument payloads for imaging crops, minerals, and other terrestrial targets. These systems typically have a flight time of about 10-15 min with a payload of 3-5 kg. Systems can be incorporated with a gimbal to minimize motion of the platform and have flight plans uploaded into the system. There are issues with optimizing a large enough power supply to prevent a sudden loss of power that can destroy expensive instrumentation and still provide adequate spatial coverage. The post-processing of imagery can be considerable and frequently a target surface is incorporated into the region of interest to account for variability in the downwelling light field.

<u>Autonomous Biofloats:</u> Considerable oceanographic research has been conducted by the OBB community on buoys, floats, gliders, and remotely operated vehicles. In the water column, bio-floats have now operated autonomously for up to 18 months consecutively, with profiling frequencies ranging from sub-diel to weekly, with depth-profiling covering the top 100 m to several 1000s meters (IOCCG 2011). These biofloats can now be equipped with a variety of physical, chemical and bio-optical sensors, can either store data or transmit data via satellite communications at any frequency, are controlled by two-way communications, are inexpensive, and can be deployed from vessels and aircrafts. A float sampling capacity and life time are a function of the programmed sampling rate and profile depth as well as physical obstacles such as topographic features at the bottom or sea ice towards the surface, though ice-avoidance algorithms have been successfully deployed in sub-Arctic, Arctic and Southern Ocean waters.

<u>Remotely Piloted Underwater Vehicles:</u> Remotely operated vehicles have been use to conduct deep sea research with photography and high definition video and coupling this technology with bathymetric and side-scan sonar (e.g., Roman et al., 2011). Hyperspectral imagers have also been mounted on underwater platforms with artificial lights to detect changes in the deep seafloor (Johnsen et al., 2013). Such technology is within the expertise of OBB and could be developed in partnership with space exploration studies that seek to investigate life in extraterrestrial oceans. Different scales of mapping can be used to address different scientific and environmental questions and also be simultaneous and complementary to one another. At a distance of 2 m above the seafloor, the platform will typically obtain a spatial resolution of approximately 2 mm. A remotely operated vehicle (ROV) is deployed and tethered from a ship during the entire deployment. The tether provides both power and communication to the vehicle and allows for on-line control of the instrument and collection of the data stream, but limits the areal coverage. An AUV is an autonomous underwater vehicle that can either be a glider or propeller-driven system. Autonomous gliders change buoyancy internally and profile the water column by converting a fraction of their vertical motion into horizontal velocity. While useful for many oceanographic applications, gliders have very low power capacity and limited sustained sampling capabilities near the seafloor.

3. Sensors

With advances in sensor and platform technology, portable platforms can be equipped with multiple sensors for simultaneous measurement of a diverse suite of parameters from both passive and active sensors. The following are a few of the sensors that could be incorporated effectively together on a drone.

A. Imaging spectroscopy.

Hyperspectral imagery from aircraft systems in visible and near infrared wavelengths is useful for monitoring changes in coastal habitats, such as seagrass and corals (Hill et al., 2014; Hedley et al., 2016) (Figure 11) and to identify concentrations and types of suspended particles in surface plumes emanating from rivers, seeps, or spills. Imaging spectrometers can also be useful for delineating coastlines and water depth in flooded coastal lands (Dekker et al., 2011).

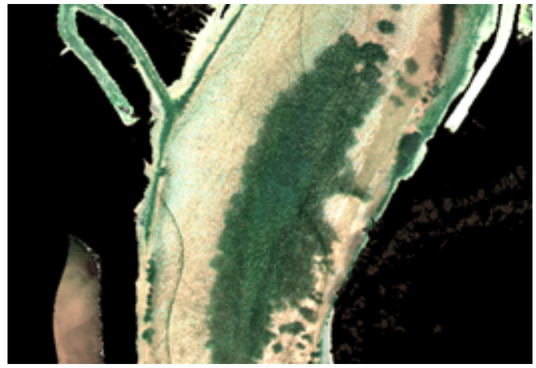

Figure 9: Retrieval of benthic reflectance of seagrass in a portion of Elkhorn Slough, CA using the airborne PRISM sensor flown on a Twin Otter aircraft. Dierssen (in prep)

Sensors should be optimized for ocean applications with a high dynamic range and signal to noise, specifically for coastal applications (Mouroulis et al., 2008; 2013; Table 1). For example, the Portable Remote Imaging SpectroMeter (PRISM) developed by NASA Jet Propulsion Lab (Table 2) was designed to be portable and has been equipped to fly on low altitude Twin Otter aircraft with 70 cm pixels and on higher flying ER-2 aircraft with 8-10 m pixels. This sensor could be adapted to be mounted on a variety of aerial autonomous aircraft as well.

Table 2: Spectrometer Characteristics

Spectral	Range	349.9–1053.5 nm
	Sampling	2.83 nm
	Resolution (FWHM)	3.5 nm typ
	Calibration uncertainty	<0.1 nm
Spatial	Field of view (FOV)	30.7°
	IFOV sampling	0.882 mrad
	IFOV resolution (FWHM)	0.97 mrad
	Cross-track spatial pixels	608
Radiometric	Range	0%–99% *R*
	Sampling	14 bit
	Calibration uncertainty	<2%
	Signal-to-noise ratio[a]	500 at 450 nm
	Polarization variation	<1%
Uniformity	Spectral cross-track uniformity	>95%
	Spectral IFOV uniformity	>95%

[a]At a single integration (167 Hz rate) and three-band aggregate (8.5 nm), 5% reflectance, 45° solar zenith, MODTRAN standard atmosphere.

B. Fluorescence lidar.

In the upper layer of the ocean, oil slicks and chlorophyll can both be detected with active fluorescence lidar. In the early 1970s, the first airborne laser fluorosensor was flown to map the extent of oil slicks (Brown & Fingas, 2003) and the technology has been refined and further developed over time (Fingas & Brown, 2014). Fluorescence lidar can be used for oil identification, and to estimate the thickness of oil films at the water surface (Li et al., 2014). Both the spectral shape of fluorescence induced from surface water and the intensity ratio of two channels (I495/I405) can be used to characterize oil spills.

C. Bathymetric lidar.

At present, the most effective means to map shallow water bathymetry is with active lidar systems (Dierssen & Theberge, 2012). Generally, two lasers are employed to estimate bathymetry: 1) an infrared laser (1064 nm), which does not penetrate water, is used to detect the sea surface and 2) a green laser (532 nm) is used to penetrate into the water column and provide a return signal from the seafloor (Quadros & Collier, 2010). In coastal waters, green light is the least absorbed and generally penetrates the deepest into the water column. Lidar measurements with an elevation accuracy of 10–30 cm can provide point measurements from 0.1 to 8 pixels per m^2. They have been successfully used to map bathymetric features, beach erosion, coral reefs, and coastal vegetation. Unlike acoustic sensors on ships, lidars can also be useful for delineating coastlines and providing a seamless transition between the land and water interface (Figure 10).

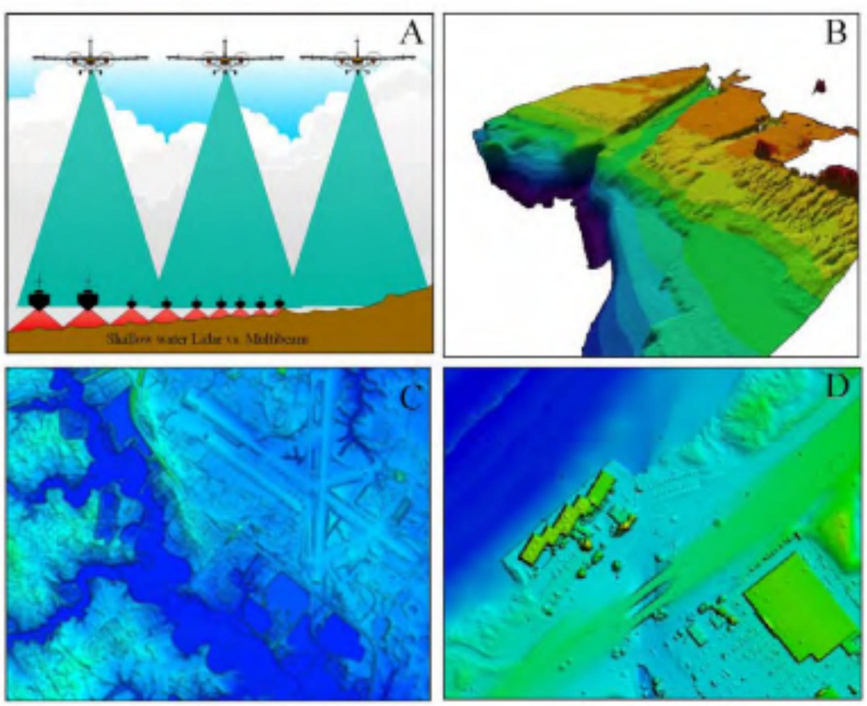

Figure 10: Adapted from Dierssen and Theberg (2012). A) Airborne lidar provides a large sampling swatch for collecting bathymetry data compared to ship-based sonar systems and B) can seamlessly blend water and land elevations in one image for precise coastline delineation. Lidar data collected in C) coastal Delaware can be used for mapping projected sea-level rise; and D) Monterey Bay for evaluating erosion patterns along a seawall jutting into the coastal zone. Images in Panel A and Panel B provided courtesy of Optech Industries. Images from Panel C and Panel D are available from the NOAA Coastal Services Center Digital Coast project.

For underwater imaging, laser profile imaging has been used from an underwater vehicle to map detailed bathymetry of the seafloor (e.g., Roman et al., 2010). A 532 nm laser was fit with a 45° spreading lens to produce a single thin laser sheet. During the survey laser images were collected at approximately 3 Hz while the platform moved at speeds up to 5 cm/s along preset track lines maintaining a constant altitude of between 1.5 and 3.0 m above the bottom.

4. Technology Needs

The technology for developing portable sensors on a variety of spaceborne, airborne and underwater platforms has advanced significantly over the last decade. However, considerable technological and software developments are required to develop high quality data from these platforms to monitor transient hazards and natural disasters along the U.S. coastal zone and beyond. These platforms could include state-of-the-art sensors such as the imaging spectrometers, fluorescence and bathymetric lidars and automated processing routines to provide near real-time monitoring capabilities. The systems would need to be well calibrated, have rapid sampling capabilities, and be coherent in terms of software for processing different types and potentially large volumes of co-located data streams. The more processing that could be conducted in real-time and transmitted back to a control center, the quicker the response. The possibility for adaptive sampling would be advantageous such that the platform could be tasked with monitoring precise locations based on the data already collected.

New and improved in-water and atmospheric algorithms are required to accurately determine the composition, quantity and extent of floating and suspended materials across diverse aquatic environments and to assess bathymetry and seafloor composition. This would include compiling spectral libraries of different pollutants and toxins, benthic and floating vegetation, suspended sediment types and new objects of interest. Atmospheric correction algorithms would be required that can tolerate more extreme conditions in water vapor, dust, and other aerosols that are common to transient events.

The technology for conducting underwater imaging requires additional advances including underwater vehicle mechanical and control system design, navigation data processing, sensor design, signal processing, image processing and mapping algorithms. Corrections must be made for platform speed and direction, dynamic positioning, pitch/roll/yaw, as well as techniques to account for the absorption and scattering by suspended particles. The database of underwater reflectance endmembers, particularly in the deep sea, is limited and needs to be quantified. Moreover, algorithms to automatically discriminate, identify, and quantify targets of interest must be developed. Adaptive sampling routines could also be optimized so that the vehicles are programmed to map the extent of targets of interest once they are identified.

For many applications, integrated modeling and data assimilation efforts will be required to develop predictions of where the threat originated and the direction and speed of movement. This may require incorporating existing datasets on bathymetry and coastal morphology with in situ measurements and various remote sensing products, such as sea surface temperature, vector winds. Expanded model testing to different regimes and type of threats would be necessary to improve skill for future predictions.

5. Ancillary requirements

The ability to deploy portable sensors in response to immediate hazards would require a dedicated facility and program. This could be modeled on the NASA airborne science program that currently manages airborne AVIRIS campaigns. The center would be responsible for maintaining the platforms, calibrating the sensors, communicating with responders, developing deployment plans, transporting equipment, collecting and processing the data with state-of-the-art algorithms, and reporting findings in a timely manner.

6 FIELD DATA AND CAMPAIGNS

An essential element of the OBB program is to develop a strong portfolio of field observations for algorithm and product calibration and validation and to provide a means for improving the quality and utility of remote sensing measurements. Field measurements must include consistent and high quality time-series observations for assessing sensor quality over time (e.g., vicarious calibration). Additional field measurements are needed to validate products in a manner ensuring accuracy throughout the world ocean and to identify the diversity of spectral properties for natural and anthropogenic constituents found in aquatic systems. Finally, field process studies are required to delimit fluxes and rates used in algorithms and models.

The aforementioned diversity of field observations is unified under the requirement for consistent data formats, including metadata, and wide access from the user community. Currently, SeaBASS is a publicly shared archive of in situ oceanographic and atmospheric data maintained by the NASA Ocean Biology Processing Group (OBPG)[2]. This archive is invaluable for algorithm development and product validation and is a critical component of all of the recommended observational strategies detailed in this Advanced Science Plan.

6.1 CALIBRATION AND VALIDATION (CAL/VAL)

The determination of ocean biological and biogeochemical quantities from low earth orbit has proven a difficult task. More than 90% of the passive optical signal measured on-orbit is derived from atmospheric scattering and is not the light emitted from the ocean. Hence, satellite ocean color observations need to accurately determine a very small ocean signal from a nearly overwhelming atmospheric one. Moreover, the signals associated with long-term trends can be very, very small and thus make the accurate detection of long-term changes especially difficult. Most of the proposed observational strategies, with the exception of suborbital surveys, involve delicate optical instruments that are launched into orbit by massive rockets and subjected to huge accelerations and vibrations and a hostile space environment. These factors compromise the validity of pre-launch calibrations for processing the resulting data streams. Currently, the MOBY buoy (Pacific Ocean near Hawaii) and BUSSOLE buoy (Mediterranean Sea) provide continuous time-series suitable for vicarious calibrations of space-based spectrometers. New technology and strategies for obtaining additional vicarious calibration data are being pursued and are warranted going into the future.

The ideal Cal/Val program strives to:

- accurately sample relevant observables in relationship to known community measurement standards and best practices,

[2] http://seabass.gsfc.nasa.gov; http://oceancolor.gsfc.nasa.gov.

- make observations routinely and consistently over a long time,
- make these observations across a wide range of biological and biogeochemical provinces,
- provide field data to a centralized data center where data are synthesized into global data sets and compared with satellite observations,
- compare vicarious instrument calibration results with on-orbit methods (such as lunar or solar viewing), and
- continue investment in coordinated field observations, new instrumentation and technology, calibration standards for all investigators, and the free, open, and easy access of all data collected in support of the Cal/Val program.

6.2 Process Studies

NASA has a long history of supporting field observations to advance our understanding of the planet and to further develop and refine remote sensing techniques. In the last decade, NASA OBB has recognized the need for conducting targeted field campaigns to reduce uncertainties in products from selected aquatic ecosystems or leading to fundamental new approaches or ideas about ocean biology and biogeochemistry. Large interdisciplinary field campaigns have involved investigations of air-sea fluxes of carbon in the Southern Ocean (SoGasEx), the biology and biogeochemistry of a rapidly changing Arctic Ocean (ICESCAPE), ship-aircraft bio-optical research (SABOR) and two Earth Venture Airborne missions: the Coral Reef Airborne Laboratory (CORAL) and the North Atlantic Aerosols and Marine Ecosystems Study (NAAMES). In addition, vertical sampling of the oceans is ongoing with optical sensors added to the current international ARGO buoy system deployed in the Southern Ocean (SOCCOM). Such an effort could be expanded globally. Another field campaign is scheduled to begin focusing on the fluxes involved in the oceanic biological pump (EXPORTS) and several other field campaigns are being considered in scoping studies (Arctic-COLORS, ICESOCC). Results from these diverse field efforts can challenge traditional ideas or paradigms about how ocean life functions or document phase shifts in aquatic communities influenced by ever-changing environmental forces.

Ongoing Cal/Val capabilities, new process studies, and data archiving capabilities are all required to maintain a healthy NASA OBB program that can continue growing in the coming decade. Such investments are maximized through national and international partnerships and by using existing infrastructure or programs.

7 MODELING & ANALYSIS

7.1 MARINE ECOSYSTEM MODELING

Modules for marine ecosystem structure and biodiversity are becoming an important part of ocean numerical models, which are often coupled to atmosphere, sea-ice and land models. These modeling systems are widely used to study climate and climate change impacts on marine physics and biogeochemistry. At finer resolutions, these models are used to address coastal, Great Lakes and estuarine applications, bloom dynamics and ecosystem responses to sea-ice changes and continental runoff inputs. In more simplified versions, numerical models have been used for investigating isolated processes, testing parameterizations such as sinking and settling, remineralization, and absorption and backscattering.

Understanding marine ecosystems under environmental stressors and the robust incorporation of this information into models are key to attributing past changes and determining future variability and vulnerability (Scheffer et al, 2001; Folke et al, 2004) in the ocean carbon cycle, ocean acidification and deoxygenation, and climate feedbacks (Doney et al., 2009; Helm et al, 2011; Bates et al, 2014). The recent 5th phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) included for the first time coupled carbon-climate interactions through explicit representation of biogeochemistry and ecosystems (Ciais et al., 2014). While these models include only rudimentary representation of physiology, biodiversity, and ecological functioning (LeQuere et al., 2005), there are exciting opportunities to improve their representativeness, robustness, and applicability to a suite of biogeochemical and ecological questions. Indeed, the latest round of Primary Production Algorithm Round Robins, supported by NASA OBB, focused in the Arctic Ocean and provided the opportunity to evaluate the skills of 32 ocean color-based models (Lee et al., 2015) and 21 regional/global circulation and earth system models (Lee et al., 2016) in reproducing primary production, in addition to certain physical and chemical variables, by comparing them to field and/or remotely-sensed values. Such exercises help the research community prioritize parameterizations as well as augment rate and flux measurements during process studies in critical regions.

NASA remote sensing provides the only globally comprehensive and multi-year long observational record to characterize and constrain these functions for incorporation into coupled models. NASA data of ocean color as well as aerosols, surface irradiance, precipitation, sea surface temperature and wind forcing help model and assess the processes that play a role in the ocean carbon cycle and affect the ocean biogeochemistry. Such processes relate to air-sea gas exchange, deposition of aerosols, dust and other chemical compounds, coastal and open ocean upwelling, continental runoff, sea-ice biogeochemistry, phytoplankton distributions and community composition. These processes are observed through remote sensing and such observations are used to validate climate models, or as boundary conditions or forcing fields. Therefore, NASA datasets have provided support and guidance in the development of more interactive components of the earth system models, e.g. wind induced changes of coastal upwelling and the associated offshore upwelling of nutrients and cross-shelf transport (García-Reyes et al, 2015), albedo changes due to chlorophyll (Gregg and Casey, 2007; Romanou et al, 2013), dust deposition and iron fertilization of the ocean (Jickells et al., 2005; Boyd and Ellwood, 2010) and the direct ballasting of minerals (Armstrong et al., 2001), wet and dry deposition of compounds such as oxidized nitrogen and reduced nitrogen that fertilize the ocean, phytoplankton sensitivity in differential sunlight absorption under sea-ice (Long et al., 2015; Manizza et al., 2011).

Specifically, remotely sensed phytoplankton properties provide a description of biodiversity and its controls globally but also regionally and across different temporal scales, from daily to monthly to interanual, and improve ecological strategies that determine rates, variability and resilience of marine ecosystems. Such strategies include characterizing phytoplankton diversity through pigment (Raitsos et al., 2008), size structure (Kostadinov et al., 2010), and ecological traits (Follows et al., 2007; Dutkiewicz et al., 2009), in addition to traditional functional type descriptions (Moore et al., 2004; Dunne et al., 2013; Gregg and Casey, 2007).

NASA datasets of both physical as well as biological properties are now utilized in assimilation modeling which aims to provide operational products for biological variables, including ocean color, phytoplankton distributions, ocean albedo, which have important use in operational weather prediction, fisheries, ecosystem response to disasters (spills, storms etc). Such models include inverse models (Anderson et al., 2000) and sequential assimilation models (Gregg, 2008).

Site or process specific models and parameterizations are critical in understanding the complex relationships between biogeochemistry and ecosystems, as well as the physical-biogeochemical interactions and including these in models. Global, high frequency observations of optical properties in the surface and subsurface ocean improve models that offer understanding of the following:

- organic carbon and inorganic particulate carbon (Behrenfeld et al., 2005) impacts on ecosystem properties
- biomass dependence on physical, chemical and ecological differences and exchanges between coastal and pelagic environments (May et al., 2003)
- improved phytoplankton phenology on decadal timescales (Henson et al., 2009)
- the biological pump (Laws et al., 2000, Siegel et al., 2014)
- harmful and nuisance plankton blooms (McGillicuddy, 2010)
- continental runoff changes and introduction of organic and inorganic nutrients and carbon into the marine environment, especially the Arctic (daCuhna & Buitenhuis, 2013; Bates & Mathis, 2009; Cooper et al, 2005)
- sensitivity to environmental stressors (e.g., hypoxia, acidification, eutrophication; Bopp et al., 2013)

7.2 DATA ASSIMILATION

As more observational and reanalysis data become available, in addition to improved computational resources and new insight on the importance of specific processes and regions, inverse modeling and new statistical analysis tools have been developed accordingly. These inform the global & regional scale modeling discussed in the previous section, as well as provide operational quality products for better estimation of albedo, phytoplankton distributions and upper ocean heating. Some of the breakthroughs in this area of research are described below.

7.2.1 Observing System Simulation Experiments (OSSE)

Constructing numerical models typically requires vast simplification of key processes. These approximations lead models to be biased, imperfect representations of nature. In spite of these imperfections, however, properly constructed models are self-consistent and provide comprehensive information about their dynamics.

Key challenges in designing sampling strategies and interpreting data from observational campaigns is to ensure that the most relevant sites are sampled, and to develop understanding for the spatiotemporal scales that individual measurements represent. Numerical models can help address these challenges; observing system simulation experiments (OSSE) are a general category of approaches to enable using models to evaluate and improve the design of new observations and observational strategies. Concerted efforts to develop OSSEs in the climate community are already underway (e.g., at NASA/GMAO; Errico et al., 2013). A challenge in this realm is that models are composed of entities that are not necessarily directly observed. For instance, satellite chlorophyll "observations" are derived from ocean color, employing algorithms that incorporate many first-principles concepts, but also many assumptions. Ocean biogeochemical models include prognostic variables for chlorophyll, which can be compared to chlorophyll estimates derived from ocean color but a more powerful means of comparison might be to simulate the actual physics of the ocean color measurements, developing a simulator model of the satellite measurements, thereby enabling direct comparisons between observations and modeled fields. There is precedence for this in the cloud physics community (ISCCP simulator).

7.2.2 State estimation and data assimilation

Mechanistic models can be used to interpolate between incomplete, often sparse, observations. Data assimilation is a collection of techniques that, generally speaking, enables models to improve their consistency with observations. Data assimilation is an essential aspect of state estimation, wherein observations that are discrete in space and time are ingested into a modeling framework, such that the modeled state is forced to match observations to the extent possible, using some algorithm to minimize a misfit cost function. There are several techniques that can be used for state estimation (3DVar, 4DVar, Ensemble Kalman filter, etc.). Applications of state estimates are extensive (e.g., analysis of trends and variability, boundary conditions, initialization of forecast experiments). The quality of state estimates is inherently limited by observational density; at present various ocean reanalysis (state estimate) products show reasonable correspondence in well-observed regions, but wildly divergent behavior in areas with limited observations (i.e., below 2000 m). Biogeochemical state estimation is an emerging application and faces several challenges. In contrast to ocean physics, there is no analog to the Navier-Stokes equations for biology, thus biogeochemical and ecological models form representations with some degree of arbitrariness. As a result, state estimation in the context of biogeochemistry is probably best paired with parameter estimation, allowing the model formulation, in a sense, to adapt based on innovations provided by observations. Experience with such applications often indicates model deficiencies, wherein, for instance, parameters that are expected to be constant, are found to vary in time when informed by observations indicating that the model likely omits important structure.

7.3 ADVANCED STATISTICAL ANALYSIS TECHNIQUES

7.3.1 Biomes

Defining coherent regions of the marine environment by common functional characteristics is a major challenge in oceanography. Since it is impossible to make comprehensive direct observations of the environment, an ability to define oceanographic regions with common functional characteristics enables scaling of limited observations. There are two approaches to biome definitions that are useful. The first and most standard is to define and apply threshold criteria to a set of variables, such as chlorophyll concentration, mixed layer depth or mean vertical velocity (e.g., Fay & McKinley, 2014; Sarmiento et al., 2004). This approach yields a top-down classification of environmental domains. An alternate approach is to allow relationships between variables to emerge within an analysis approach that does not make explicit a priori assumptions about the dominant factors. Self-organizing maps are an example of such an approach that is bottom-up and can be applied to biome classification. The types of questions that can be asked include: "which regions operate with a coherent set of similar dynamics?"

7.3.2 Clusters and neural networks

Various nonlinear approaches can be applied to identify mechanisms driving variability in a given system that can then be used, for example, in the biomes definition described above. This concept is being used to generate a time history of biogeographic 'seascapes' in the context of the Marine Biodiversity Observation Network (MBON) of the Group on Earth Observations (GEO). "Seascapes" are estimates of biogeographic areas derived from a thematic classification of multidisciplinary satellite data (Oliver & Irwin, 2008; Kavanaugh et al. 2014 and 2016). These provide a coherent picture of the status and change in physical, chemical, and biological ecosystem characteristics. Rather than using a correlative framework, neural networks or cluster analysis avoid the inherent assumption of linearity, and are thus potentially powerful tools applied to highly nonlinear ecosystem dynamics.

Natural climate variability is characterized by broad-band fluctuations in key variables of interest to the marine biology and biogeochemistry research community. Natural variability presents challenges to prediction as well as detection and attribution. On some timescales, variability is essentially nondeterministic, in the sense that the chaotic behavior of the climate system limits predictive horizons: small uncertainties in initial conditions grow to dominate solutions and predictability is lost. A related issue involves detecting the signal associated with human-driven influence on the climate system. Decadal and multi-decadal trends are present in marine variables due to natural variability; this noise inhibits efforts to attribute long-term trends to secular climate change. Both these issues can be addressed, to some extent, with large ensembles of coupled Earth system models. Coupled models generate natural variability that is characteristic of nature, but evolves independently within a given integration. Combining multiple realizations of historical or future forecast periods, large ensembles enable powerful inferences about the role of natural variability in driving dynamics.

8 EDUCATION/PUBLIC OUTREACH

Breathtaking views of Earth, the Water Planet, from space have captivated the imaginations of people around the world and increased awareness of both the beauty and the fragility of our planet. Satellite images of the global ocean have allowed us to explore the ecology, biogeochemistry and hazards of previously uncharted waters, revealed the coupling between physics and biology, the constant exchanges between the land and the ocean, as well as the complex interactions and feedbacks between Earth systems and human societies. These images of the Earth's ocean not only result in new knowledge and discoveries, but provide valuable assets to engage public audiences, inform decisions, inspire students, and encourage the pursuit of science, technology, engineering, and math (STEM) studies.

NASA's education program strives to "inspire and motivate students to pursue careers in science, technology, engineering, and mathematics" by supporting education in the Nation's schools and to "engage the public in shaping and sharing the experience of exploration and discovery" by supporting informal education and public outreach efforts. NASA's goals for education across the agency are to:

- Contribute to the development of the science, technology, engineering and mathematics (STEM) workforce in disciplines needed to achieve NASA's strategic goals through a portfolio of programs,
- Attract and retain students in STEM disciplines through a progression of educational opportunities for students, teachers, and faculty, and
- Build strategic partnerships and linkages between STEM formal and informal education providers that promote STEM literacy and awareness of NASA's mission.

The complexity of the Earth as a coupled system where the ocean interacts with the atmosphere, land, biosphere and human components, presents unique opportunities for STEM education that in many cases transcends the traditional approach of teaching disciplinary science. Research in Ocean Science and Earth System Science at NASA has become increasingly multidisciplinary as well as increasingly focused on the societal benefits of research results, demanding collaboration of experts not only in traditional sciences, but also in social sciences, computational sciences, informational technology, and policy. New tools and resources are needed for addressing these interdisciplinary needs in research and education.

Water on Earth shapes every aspect of our lives. Thus, the benefits and value of observing, understanding and predicting processes in the ocean environment extend beyond basic science and research. Satellite oceanography over the past decades has resulted in remarkable tools and resources, including comprehensive databases, models, software, data analysis and visualization tools that have provided unique assets for STEM education and public outreach. The development of new remote sensing technologies and improved ocean sensors with advanced capabilities discussed in this document will provide new opportunities for increased engagement of satellite data user communities and contributions to formal and informal public education. More knowledge-sharing tools, training opportunities, and public outreach resources will be needed to ensure that NASA's new ocean datasets become readily available and suitable for a diverse audience and a wide range of users from teachers, to students, decision makers, managers and other stakeholders. Increased outreach and user engagement would highlight the societal value and benefits of ocean observations from space and result in greater return on NASA's science and technology investment.

9 PARTNERSHIPS

The NASA OBB program will continue to engage the national and international basic and applied science communities to address a number of objectives. Specifically, coordination with the Committee on Earth Observation Satellites (CEOS) is critical to cooperate in the provision of launch services and observing technologies; in particular, the possibility of merging data from different sensors and establish virtual observing constellations is unique. Coordination with the International Ocean-Colour Coordinating Group (IOCCG) will continue to promote the development and application of ocean-color data, and develop community consensus on radiometry (OCR) and products. These collaborations will ensure that necessary data streams for observational and forecasting systems are sustained, and that the international community can develop and advance priority science questions, pursue partnerships in space-based sensor development and measurement capabilities, and synergize field collection and processing, including vicarious calibration and data product validation activities.

The technology, data and models outlined in this Advanced Science Plan are integral to the many and diverse national agencies that supply observational and forecast data essential for our society. NASA OBB will continue to partner with federal agencies that use the portfolio of earth observations including the military services and combatant commands of the U.S. Department of Defense, the National Weather Service, the U.S. Environmental Protection Agency, the National Oceanic and Atmospheric Administration, the National Marine Fisheries Service, U.S. National Park Service, and the U.S. Fish and Wildlife Service. In addition, the products from these technologies are used in regional and local governmental agencies that are responsible for providing clean water, zoning development of coastal lands, hazard detection and mitigation, and maintaining recreational uses of lakes, rivers, beaches, and coastal waterways.

In addition, NASA OBB participates in and contributes to various U.S. programs (e.g., Climate Change Science Program, U.S. Ocean Action Plan committees, U.S. Integrated Earth Observation System), which the implementation of this Advanced Science Plan will continue to support. The National Oceanographic Partnership Program (NOPP) helps to ensure that these contributions are shared across other federal agencies, as appropriate. Additionally, NASA likewise partners with other U.S. agencies to promote operational implementation of research and development capabilities and results as deemed beneficial in support of user needs (as discussed further below). In this manner, this Advanced Science Plan does not represent a stand-alone vision.

Implementation of this strategic Advanced Science Plan will represent a significant contribution in both research and technology development by NASA to an overarching global ocean observing system, and furthermore as part of the emerging Global Earth Observing System of Systems (GEOSS). In the GEO context, NASA will make important contributions to the development and application of the Marine Biodiversity Observation Network (MBON) and Blue Planet. Fundamental scientific discoveries will result, as well as significant benefits to society. In this broader observing system context, this Advanced Science Plan will both complement and leverage other space and in situ-based components of these systems, and as such broad partnership opportunities abound as briefly highlighted below.

Ocean observing systems (including the Ocean Observatories Initiative (OOI) and the Integrated Ocean Observing System (IOOS)), will be part of the U.S. contribution to the Global Ocean Observing System (GOOS) and part of the GEOSS, that by definition will need to consist of integrated observations from both in situ and remote assets. This OBB Advanced Science Plan contains a vision for novel, science-driven biological and biogeochemical measurements of the open and coastal ocean from space that will support fundamental research as well as enable new and improved user-driven applications. As such, partnerships that help bridge the space-based research and operational domains and facilitate the transition of knowledge and capabilities between these communities are envisioned; likewise cross-cutting community partnerships that foster linkage of remote sensing and in situ observations.

Crucial, nested ocean observing capabilities in partnership with the international space research community and space agencies needs to be quickly built out and then sustained over time. This requires attention to the transition of capacities and technologies from research to operational agencies. To the extent possible, NASA OBB will continue to engage with national and international partners contributing individual elements, coordinating standards and calibration/validation strategies, sharing data, and avoiding measurement gaps/redundancies under the auspices of the GEOSS and CEOS.

Moving beyond a strictly disciplinary focus, there are opportunities to partner with other Earth observing programs, particularly within NASA. For example, there are significant benefits (and cost savings) to be gained by working with NASA's Terrestrial Ecology Program scientists toward implementation of a high resolution coastal imager that can also be used to provide accurate vegetation cover assessments or resolve functional type mixtures. Likewise, accurate measurement of aerosol properties is a crucial element in support of ocean biological and biogeochemical observations, affording partnering opportunities with the atmospheric science community. Many NASA technologies, including various active and passive radio and microwave sensors, infrared sensors, and various other active and passive visible light sensors provide important geophysical and ecologically-relevant information for ocean studies. These needs should be considered in conjunction with those of the solid Earth, cryological, atmospheric, and terrestrial science communities to develop missions that can satisfy multiple requirements and multiple disciplines.

10 Summary Table

Science Questions	Measurement & Assessment requirements	Platform/Infrastructure Requirements
(1) *What processes drive change in ecosystem structure and biodiversity and how do contemporary changes in these globally expansive ecosystems inform improved managements practices, predictions of change, and global ocean stewardship?*	▪ Ocean color missions paired with atmospheric sensors ▪ Information on vertical dimension, day and night ocean measurements, retrievals between and under clouds and through aerosols	▪ Lidar with UV and visible excitation wavelengths and capability to directly separate absorption and backscatter (e.g., HSRL-type approach)
	▪ Repeated observations on sub-daily to monthly time scales	▪ Constellation of GEO satellites or constellation of LEO with different equator crossing times
	▪ Capability to forecast changes and evaluate the implications of stock and rate changes	▪ Ecosystem modelling ▪ Underwater portable sensors
(2) *How are the diversity, function, and geographical distribution of aquatic boundary habitats changing?*	▪ Improved spatial, temporal, and spectral resolutions of satellite ocean color sensors ▪ Complete annual coverage of polar systems	▪ GEO and LEO satellites, suborbital systems, and models ▪ Robust data processing and distribution infrastructure
	▪ Improved bathymetric characterization of coastal areas	▪ Lidar with measurement capabilities as in Question 1 ▪ Suborbital and underwater platforms
	▪ Capability to assess, manage and forecast impacts of environmental changes	▪ High temporal space-based measurements in combination with operational models
(3) *How do carbon and other elements transition into, between and out of ocean pools? What are the quantitative links between ocean biogeochemical cycles and climate?*	▪ Observation of surface and vertically-resolved ocean geophysical properties at high spatial to global resolution and high temporal resolution ▪ Access to high-precision observations of atmospheric composition ▪ Improved modeling of elemental stocks and transfer rates informed by remote sensing observations ▪ Synthesize observations, test hypotheses, and forecast biogeochemical cycles	▪ LEO or GEO satellite constellation as in Question 1 ▪ Satellite lidar with measurement capabilities as in Question 1 ▪ Physical, optical, and biogeochemical observations using in situ autonomous platforms ▪ Hyperspectral passive ocean color and multiwavelength lidar observations from suborbital platforms ▪ Numerical models that include coastal, cryological, and riverine outflow at high spatial resolution

(4) *How can knowledge of the spatial extent, dispersion, intensity, and frequency of transient hazards and natural disasters in the aquatic environment improve forecasting and mitigation?*	▪ Improved temporal, spatial, and spectral resolution imagery ▪ Improved assessment of threats in high latitude/remote regions ▪ In situ time-series measurements and improved forecasting ▪ Advanced atmospheric observations for improved remote sensing retrievals under complicated aerosol conditions ▪ Improved forecasting skills	▪ Portable sensors on orbit and suborbital, including assets on and in water ▪ Active and passive sensor technology to assess water depth, pollutants, harmful algal blooms and other relevant properties ▪ Concomitant field data and remote sensing imagery ▪ Database of habitats and bathymetry to assess impact of hazards ▪ Integration of biophysical models with in situ and remote sensing data

11 References

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